Vehicle Positioning Trade Study for ITS Applications

www.its.dot.gov/index.htm

Final Report — April 3, 2012

Publication FHWA-JPO-12-064

U.S. Department of Transportation

Produced by ARINC Incorporated
Under Contract DTFH61-10-D-00015
Task Order T-11001
ITS Joint Program Office
Research and Innovative Technology Administration
U.S. Department of Transportation

Technical Report Documentation Page

1. Report No. **FHWA-JPO-12-064**	**2. Government Accession No.**	**3. Recipient's Catalog No.**	
4. Title and Subtitle Vehicle Positioning Trade Study for ITS Applications Final Report		**5. Report Date** August 30, 2011 **6. Performing Organization Code**:	
7. Author(s) Bruce Abernethy, ARINC Incorporated Scott Andrews, Cogenia Partners Gary Pruitt, ARINC Incorporated		**8. Performing Organization Report No.**	
9. Performing Organization Name and Address ARINC Incorporated 2551 Riva Road Annapolis, MD 21401		**10. Work Unit No.** **11. Contract or Grant No.** DTFH61-10-D-00015	
12. Sponsoring Agency Name and Address Operations Research & Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		**13.Type of Report and Period Covered** Final Report August 30, 2011 **14. Sponsoring Agency Code**	
15. Supplementary Notes FHWA Contracting Officer’s Technical Representative (COTR): James Arnold			
16. Abstract This report presents positioning requirements and technology review results for ITS applications.			
17. Key Words ITS, Positioning System		**18. Distribution Statement** No restrictions	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 195	**22. Price**

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Acknowledgements

ARINC and its team members on this task would like to thank James Arnold and Deborah Curtis of FHWA for their guidance in the conduct of this research and preparation of this report, and the members of the stakeholder groups, who provided valuable feedback on the ITS applications and positioning technologies selected for evaluation. We would also like to acknowledge the various technology suppliers who provided technology and product information that supported the analyses described herein, and the various research sources referenced throughout this document.

Table of Contents

Page

Table of Figures

Table of Tables

Executive Summary

This report summarizes the results of a detailed positioning study intended to evaluate various positioning technologies and their applicability to a suite of location dependent vehicle safety and mobility applications. The initial phases of the study included a detailed summary of the applications, and a market scan of available positioning technologies. The applications examined included 132 different applications distributed in seven broad categories:

- Hazard, Information, and Traffic Control;
- Vehicle Guidance;
- Vehicle Management;
- Fee Determination and Collection;
- Traffic Management;
- Vehicle Security, Safety and Maintenance Support;
- Automated Vehicle Support.

The analysis included development of the application concepts and interviews with stakeholders to ascertain the general requirements for these different applications. The results of this phase of the project were presented in the Task 2 report.

A market scan of available positioning technologies was then performed. This included a review of publications related to sensor development and testing as well as a scan of manufacturer's product specification sheets. Manufacturers were contacted to obtain product specifications. The scan included sensors that provided absolute position (e.g. GPS) as well as relative position (e.g. distance sensors such as RADAR), and covered both vehicle-based sensors as well as infrastructure-based sensors.

The scan addressed a wide variety of positioning systems. These included:

- Currently used roadside sensing systems such a loop detectors, etc.;
- RADAR, LIDAR and ultrasonic relative positioning systems;
- Imaging systems;
- GPS systems, Inertial and hybrid inertial/GPS systems;
- Wireless positioning systems;
- Digital mapping systems.

The technologies were examined at a high level and general performance capabilities were summarized. From this large set, a short list of especially promising technologies was developed for more detailed analysis. These technologies are:

- RTK and Carrier Phase GPS;
- Digital TV ranging;
- Infrastructure Based Ranging Responders;
- Infrastructure RADAR/LIDAR;

- Vehicle ranging (RADAR/LIDAR);
- Video systems.

Generally, these systems break down into absolute positioning systems (GPS, Digital TV, infrastructure RADAR/LIDAR, and infrastructure based video systems) and relative positioning (vehicle RADAR/LIDAR, and vehicle based video systems). The accuracy of the ranging systems was found to be surprisingly good. In applications where accurate relative position is needed, these technologies generally provide a more reliable and more accurate position estimate than using comparative absolute positions (for example exchanging GPS positions). They have an added advantage that they do not require the other vehicle to be equipped and/or functioning to operate. In fact, through the course of this analysis, it became clear that the reliance on other vehicles to provide their position can be represented as an availability specification. If the probability that the other vehicle is equipped is, for example, 20%, then this is the same as a positioning system that is only available 20% of the time. This was a somewhat sobering finding that draws into question the viability of cooperative systems operating independently from other sensors.

While video systems were not studied in great detail, the current state of the art, driven, interestingly, by the gaming and animation industries, appears to be becoming quite competitive. It has the added advantage of providing much higher levels of scene acuity and, as scene interpretation capability matures, this technology is likely to become more viable.

The table below summarizes the various positioning approaches.

Positioning Approach	Characteristics
GPS	• Core Positioning Technology; • No Superior Vehicle Positioning Technology Identified (Cost to User and Performance); • Improvements in OEM Grade GPS Location Accuracy and Ability to Obtain Integrity is Within State of the Art with Investment in Large Scale Integration.
GPS+IMU	• Best of all Positioning Solutions; • Provides Position Needed for Safety Applications with Temporary Loss of GPS Satellite Signal; • Supports Projection of Vehicle Position in Future Time using Position, Velocity and Acceleration Vectors; • GPS Minimizes IMU Drift; • Integrated MEMS with GPS Emerging onto the Market with Much Lower Cost.
Relative Ranging	• RADAR, LIDAR, Video, and Ultrasonic Technologies; • Require Vehicle Position/ Dynamics Inputs for Tracking Reference;

	• Issues with Probability of Detection, Probability of False Alarm, Revisit Time & Track Latency to Meet Safety Needs.
Sensor Fusion	• Improves Probability of Detection and Reduces False Alarm Rate; • Improves Integrity; • Adds Latency and Cost; • Not Readily Available on the Market.

The GPS findings were somewhat surprising. The initial examination focused on the high accuracy available from carrier phase systems. This is often referred to as RTK, where the carrier phase information is provided to a mobile receiver (called a "rover") by a fixed high performance base station. The issue with these systems is the need for a relatively large number of fixed base stations and, more importantly, the problem of communicating the correction and carrier phase information to the rover. This approach is not practical for vehicles. A different solution that correlates the change in carrier phase to changes in position was also examined. This approach, sometimes referred to as "carrier phase smoothing", was found to produce exceptionally good results from low cost code phase receivers. It appears that this approach combined with conventional hybrid IMU integration may provide a means for achieving sub meter position accuracy without ultra-high performance (and very expensive) hardware. It is recommended that this approach be examined in more detail to understand the startup performance (i.e. the time from startup to a high accuracy fix), the dynamic performance (the ability to maintain a solution at speed and under lateral acceleration), and the robustness in difficult radio reception environments (e.g., urban buildings, trees, etc.).

All of the GPS approaches studied benefit from external corrections. Self-contained units are capable of providing high performance, but only under the proper conditions, and typically only after some time has passed, so for vehicle applications it appears that external correction information is essential. The scope of correction information depends on the type of receiver. It does not appear that a full blown carrier phase receiver is required, but some form of carrier phase capability coupled with high quality timely corrections is likely to be the optimal solution. A key issue is the means for delivering this correction information. Correction information is provided free by the US Coast Guard, and by the FAA. The Coast Guard system provides radio beacons in coastal areas, and the FAA provides differential corrections over the Wide Area Augmentation System (WAAS) using a satellite delivery scheme. Both of these systems have drawbacks. The U.S. Coast Guard system is not intended for precision positioning, and is only available in coastal areas. WAAS is generally available about 95% of the time, but the reference stations are relatively sparse, and the corrections may not always be effective.

Several private services are also available. For example, the Trimble OmniSTAR system is a high- performance DGPS positioning service aimed at a wide range of industries including agriculture (precision farming), mining and land survey, crop dusting, geophysical surveys and autonomous vehicle operations. OmniSTAR, however, is expensive with typical subscriber fees between $800 and $1200 per year per subscriber.

Other approaches need to be considered, possibly making use of the communications systems that are providing other safety information (e.g., DSRC, LTE, etc.).

A key finding is that GPS receivers are dominated by market forces more than technology. Discussions with receiver manufacturers indicates that the high cost of higher performance units is more the result of amortizing development costs over a relatively small market than it is inherent in the cost to manufacture the equipment. Many of the higher accuracy systems also include many features that add cost, but are not related to the accuracy of the basic system. This is illustrated in the table below.

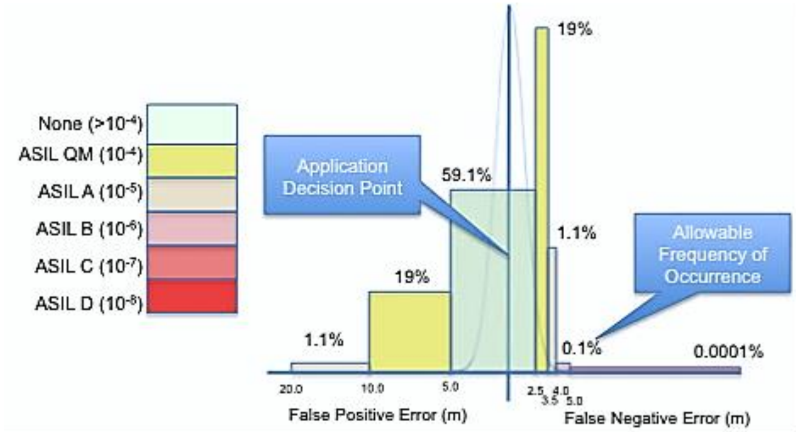
Comparative GPS Receiver Characteristics

Position Detection Approach	Signals Used	Accuracy (95% Error Radius)	Price Range ($)
C/A Code Phase Only	L1 Only	10.0 m to 15.0 m (49.2 to 32.8 ft)	$30-$70
C/A Code Phase Only with External Differential Corrections	L1 Only	3 m to 5 m (10.0 to 16.4 ft)	$250-$350
C/A Code Phase Only (internally developed atmospheric corrections)	L1/L2 (or L5)	2.0 m to 3.0 m (6.4 to 10.0 ft)	N/A
Carrier Smoothed C/A Code Phase with External Differential Corrections	L1 Only	1.5 m to 2.5 m (5.0 to 8.2 ft)	N/A
Carrier Smoothed C/A Code Phase with High Accuracy External Differential Corrections	L1 Only	0.2 m to 1.0 m (0.6 ft to 3.3 ft)	N/A
Carrier Smoothed C/A Code Phase (internally developed atmospheric corrections)	L1/L2 (or L5)	0.2 m to 1.0 m (7.2 in to 3.3 ft)	$2K-$15K
Carrier Phase RTK	L1, C/A	1.0 cm (0.4 in)	$15K-$100K

Source: ARINC April 2012

The study also resulted in the development of a process for applying the Automotive Safety Integrity Level (ASIL) concept described by the ISO 26262 standard to vehicle positioning. ASIL defines the acceptable level of failure in a system in terms of the frequency that the failure might be experienced, the severity of the failure (i.e. the consequences of the failure), and the controllability of a failed situation. This approach allowed the systematic determination of tolerable position errors together with their frequency of occurrence for numerous classes of safety applications. It also proved useful as a way to derive usable positioning requirements (both accuracy and error distribution) directly to the applications independently from the error characteristics of specific positioning technologies.

An example of the approach is shown in the figure below.



Relationship Between Position Errors and ASIL Levels (Application Dependent)
Source: ARINC April 2012

In summary, it appears that for relative positioning, the most effective approach today is to use LIDAR ranging. These systems are reliable and very accurate, but can be somewhat expensive. RADAR systems are a potential lower cost alternative, but issues relating to RF interference and spatial acuity argue for LIDAR as the more attractive solution if cost issues can be overcome. These relative ranging systems also exhibit nearly 100% availability (hampered only by severe weather), as compared to cooperative communications based systems that will exhibit less than 20% availability for at least the first decade following an industry-wide commitment to production. For absolute positioning, it appears that the differentially corrected GPS using a carrier phase smoothing approach holds the greatest potential. GPS systems of this type are generally not commercially available, but experimental tests have indicated that these techniques may provide high accuracy positioning at low cost. In general, to maintain low receiver cost, external corrections will still need to be provided.

Chapter 1 Introduction

The focus of this project is to identify ITS applications requiring vehicle position, conduct a market scan of positioning technology, conduct an analysis of the most promising positioning technology identified in the market scan and identify the positioning applications met by the technology. The Task 2 report from this project identified applications and associated positioning requirements. The Task 3 report provided the results of the market scan related to positioning technology and short listed the technology based on performance, life cycle status, supportability, reliability and other factors, including results of field testing of the technology. Stakeholder inputs related to applications requiring positioning information was used during Task 2 and stakeholder inputs were used where needed during Task 3 and 4.

This report summarizes the results of Task 4 of the positioning project and provides the findings and recommendations in final report form, as required by Task 5. The Task 2 and Task 3 reports are included as appendices.

Technologies analyzed in greater depth in this phase included:

- Global Positioning System (GPS);
- Inertial Measuring Unit (IMU);
- GPS-IMU Integration;
- RADAR;
- LIDAR;
- GPS Augmentation using Digital TV Broadcast Towers;
- Ultra wideband wireless ranging;
- Map Matching.

In accordance with the project's kickoff meeting and scope of service, both infrastructure based and vehicle based sensors were addressed. With the average length of vehicle ownership now exceeding ten years, it will take several generations of vehicles before the majority of vehicles on corridors would be equipped with advanced ITS features and associated equipment. In addition, with private vehicle owners having a tendency to delay repair of equipment that does not prevent the vehicle from operating, there is a high probability of vehicles with non-functioning ITS equipment and that cannot automatically interoperate with other vehicles (V2V) and with the infrastructure (V2I), which will be on corridors. For this reason, infrastructure related sensors will provide an important safety function.

GPS and IMUs are generally used to provide absolute vehicle position. In vehicles RADAR and LIDAR provide relative location to targets of safety concern, and using communications to share position or pseudorange data, GPS/IMU systems can also provide relative positioning. Both RADAR and LIDAR tracking systems require vehicle position and velocity vector inputs to enable correlation of received sensor return signals with previous return signals. When deployed as an infrastructure related sensor, both RADAR and LIDAR can be geo-referenced and provide a target report translated to geo-location and can also provide a location relative to a safety location of interest, such as the stop line of an intersection. Similarly, using a vehicle GPS/IMU instantaneous position as a reference, vehicle RADAR and LIDAR signal returns can be geo-referenced but not to the accuracy that can be achieved using a stationary infrastructure installation location.

Some infrastructure RADAR and LIDAR sensors are designed to detect vehicles at specific locations on a corridor, providing presence, vehicle count, headway, speed and classification. Because the operational background is constantly changing (because the vehicle is moving), RADAR and LIDAR sensors for vehicle applications typically have higher performance requirements compared with sensors specifically designed for infrastructure applications. These requirements include higher levels of spatial resolution required to differentiate targets from background clutter, and higher levels of range and range rate accuracy required to support control applications such as cruise control. For example, in order to avoid noticeable speed fluctuations in adaptive cruise control, the sensors must be able to resolve speed to less than 1%, or about 1 foot per second.

In general, range requirements for infrastructure and vehicle radar systems are similar, but the spatial acuity requirement for vehicle sensors is much higher. Short range infrastructure sensors may only need to detect the presence of a vehicle, while short range vehicle sensors need to resolve much smaller targets. For example, a rear warning (back-up) radar must be able to warn if a child's tricycle is in the vehicle path, but not warn if the lawn mower is parked in the garage just to the side of the vehicle. This represents a spatial resolution of less than about 0.5 meters.

Where information was available, latency associated with the sensor and sensor position measurement is considered. Scan frequency of the sensor determines revisit rate and thus position update of a target of safety concern. The tracking function of a sensor requires target identification, track initiation, and target track update, all of which has a finite processing time. When the target is no longer within the sensors field of view, the track is extinguished based on an established signal processing criteria (usually a finite period of time where the target signals associated with a specific target is no longer received). Fusing one sensor with information from another sensor to reduce false alarms and to improve the confidence and integrity of the target report also requires processing time and results in latency.

Different vehicle manufacturers utilize different sensor and navigation system architectures and use different hardware and software suppliers. Thus there is a difference between vehicles in the target detection, identification, and tracking algorithms and integration with the navigation and human interface (HMI) of the vehicle. Different sensor manufacturers have sensors with different emitter beam widths, pulse widths, scan rates, and other parameters (including number of targets tracked and target track update rate); thus ITS vehicles are generally likely to be implemented in a wide variety of ways, with a subsequent variation in capability. For connected vehicles to operate in a predictable manner, common operational and minimum performance standards for applications that rely on interoperability must be developed.

This report will review applications requiring positioning and provide a refined analysis of positioning accuracy requirements. Sensors are investigated to a more extensive level compared with that associated with the market scan conducted during Task 2. Sensors performance will be compared with applications requirements and compatibilities and incompatibilities identified.

Included in the appendix of this report is the technical memorandum provided related to operations and maintenance considerations of the positioning technology. This document addresses maintenance considerations as related to commercial and jurisdictional fleet vehicles as well as the private owner.

Measurement accuracy of a sensor will be considered. Definition of some of the sensor parameters includes:

- *Accuracy* **-** The degree of conformance between the estimated or measured position of a platform at a given time and its true position. Positioning system accuracy is usually presented as a statistical measure specified as the radius of a circle or sphere centered on the actual position within which a specified percentage of the position estimates are expected to fall.
- *Confidence Level* **–** The probability that the estimated position measurement lies within a circle or sphere of a specified radius centered on the actual position. .
- *Integrity* **-** The measure of the trust that can be placed in the correctness of the information supplied by a positioning system. Integrity includes the ability of the system to provide timely warnings to users when the system is unable to provide the required level of position accuracy.
- *Availability* **-** The availability of a positioning system is the percentage of time that the services of the system are usable. In the case of a radio navigation service, signal availability is the percentage of time that positioning signals transmitted from external sources are available for use. Availability is also defined in terms of the reliability of the sensor in terms of mean time between failures (MTBF) divided by MTBF plus mean time to repair (MTTR). MTBF is also considered a reliability measure and MTTR a maintainability measure.
- *Probability of Detection***:** Refers to the probability that a target within the field of view of the sensor will be detected and reported. This typically applies to a relative positioning sensor.
- *Probability of False Alarm*: Refers to the probability that the target reported does not exist as reported. This typically applies to a relative position sensor.

Chapter 2 Positioning Technology Review

1.1 Summary of Positioning System Technology

The Task 3 report of this project provided a detailed market scan of positioning technologies and systems available for both infrastructure and in-vehicle applications. The technologies examined are listed in Table 1.1-1 below.

Table 1.1-1. Positioning Technologies Examined in Task 3

Infrastructure Positioning Systems	Vehicle On-Board Positioning Systems

• Inductive Loop
• Pneumatic Tube
• Fiber Optic
• Magnetometer
• Active Infrared (LIDAR)
• Passive Infrared;
• RADAR;
  ○ FMCW
  ○ Doppler
  ○ Ultra Wideband
• Ultrasonic;
• Passive Acoustic
• Video Detection Sensors (VIDS)
	• RADAR
	• LIDAR
	• Video Imaging and Image Processing
	• Ultrasonic
	• Global Positioning System (GPS)
	• Inertial Measurement Unit (IMU)
	• GPS-IMU
	• Digital Map Matching
	• Digital TV Broadcast Tower Ranging
	• Cellular Tower Ranging and GPS Augmentation
	• UWB Ranging

Source: ARINC April 2012

The most promising of these technologies were short listed for more detailed examination in Task 4. The criteria for inclusion in this short list were:

- Applicability compatibility with applications requiring vehicle position as developed in Task 2 of this project
- Cost of equipment trending down
- Products emerging, available and growing in capability
- Systems can operate effectively in expected environment (i.e., weather conditions)
- Systems applicable to roadside, vehicle, or both
- Systems can be configured to serve a variety of applications, or serve a single high priority application
- Systems do not require subscriptions.

The technologies to be examined in Task 4 are summarized in Table 1.1-2 and Table 1.1-3 below.

Table 1.1-2. Short List of In-Vehicle Positioning Technologies

Positioning Type	Technology	Rationale
Absolute	RTK and Carrier Phase GPS	Very high accuracy; unclear what drives costs; May have substantial impact on quality of GPS based positioning accuracy
	Reference Station Corrected GPS	Generally high accuracy; Requires reference station network, and means for communicating correction data.
	GPS Integrity and distributions	Potentially viable improvement, not currently being used, but easily possible to implement
	Non-GPS Wireless (e.g., digital TV ranging or UWB Ranging)	Low cost, effective, easy to implement; May have substantial impact on quality of GPS based positioning accuracy
Relative	On-Vehicle ranging (RADAR/LIDAR)	Already partially available; Accurate; Could be integrated into DSRC based communications to supplement situational awareness.

Source: ARINC April 2012

Table 1.1-3. Short List of Infrastructure Positioning Technologies

Positioning Type	Technology	Rationale
Absolute	RADAR/LIDAR	Accurate, can detect all vehicles, cyclists and pedestrians
	Video	Accurate, inexpensive, can be integrated with existing TMC systems;
	Ultra Wideband RADAR	Specialized high accuracy, low cost RADAR system
	Roadside Based Tags (Ultrawideband Transponders)	Inexpensive; can improve accuracy of GPS/DR systems, especially in critical areas like intersections
	Provision of GPS Enhancements (e.g., RTK info)	Very high accuracy; unclear what drives costs

Source: ARINC April 2012

Since many of these technologies are applicable in both infrastructure and in-vehicle applications, these applications have been combined in the following sections. Where applicable, we have identified any characteristics or limitations that are unique to these application environments.

The following sections include:

- Global Positioning systems, with an emphasis on Carrier Phase based systems;
- Digital TV Ranging to supplement GPS;
- RADAR systems;
- Ultrawideband RADAR systems;
- LIDAR systems;
- Passive Tag systems;
- Video systems.

While not on the Task 3 short list, we have also included a discussion of Hybrid GPS/IMU systems because most on-vehicle GPS systems include inertial support to smooth the position data and to overcome short GPS outages such as in tunnels and parking structures, and a discussion of digital mapping technology because most absolute positioning systems depend on the accuracy of these maps to relate absolute position to relevant real world features, such as the roadway.

There are a number of products on the market that are designed and packaged to meet the SAE defined requirements of light and heavy vehicles. From a size, weight and power standpoint, existing vehicle sensors generally comply with vehicle requirements

Similarly, there are a number of products on the market that comply with the infrastructure environment as defined by NEMA TS-2 and Caltrans Transportation Electrical Equipment Specifications (TEES) from an environmental and power interface standpoint. From an infrastructure standpoint, sensors are emerging on the market compliant with the national Transportation Communications for ITS Protocol (NTCIP 1209, Transportation Sensor Systems). Similar common interface standards are needed for vehicle sensors.

Some video and LIDAR sensors may have temperature specifications that are not in full compliance at the upper end with both SAE vehicle and NEMA TS-2/Caltrans-TEES infrastructure equipment specifications. Similarly, both video and LIDAR sensors offered by manufacturers, may not comply with shock and vibration specifications of SAE.

Previously mentioned was the fact that vehicle sensors need vehicle motion inputs to support target track correlation; also vehicle motion information is required to stabilize the sensor in vehicle role, Pitch and yaw. Vehicle sensors also require a common reference point and position offsets from the reference point must be considered in sensor installation and calibration.

1.2 Key Positioning System Findings

1.2.1 Global Positioning System Findings

Extensive research indicates that it should be possible to obtain accuracy levels well within the requirements for most of the applications considered using low cost devices.

An essential element of achieving higher accuracy is the availability of correction data to remove a variety of systematic errors. This can be accomplished using reference station corrections that can compensate for a wide variety of errors. For example, tests of the HA NDGPS system using carrier smoothed code phase receivers confirm that accuracies on the order of 20 cm are possible. These systems, however, require the availability of an array of reference stations and the ability to deliver correction data to receivers within about 200 km. Because the United States is so large, providing uniform coverage for such corrections is challenging and expensive. Sustainable funding for the NDGPS system has been uncertain for some time, and attempts to fund an expansion of the nationwide high accuracy corrections/augmentation system have been problematic.

An alternative to current corrections systems may be to include reference station corrections as part of the overall communications systems used to support the applications. For example, the same communications system used to deliver mobility or safety information could also be used to deliver correction information. While this approach does not eliminate the cost of the reference stations, it does substantially reduce the cost of distributing the information.

The accuracy achieved using differential corrections and some form of carrier phase code smoothing appears to be well within the reach of low cost receiver implementations. This accuracy appears to be achievable without expensive low noise receivers or miniaturized atomic clocks. However, there are no commercially available low cost units able to provide this level of accuracy. This appears to be primarily a market issue. The low cost units available today are aimed at consumer markets that do not require better than a few meters of accuracy (examples are personal or boat navigation, sports devices, etc.). Even in the automotive domain, the market is dominated by navigation systems that are able to function well with tens of meters of positioning accuracy. In contrast, available high accuracy systems appear to be primarily aimed at the survey and instrumentation markets, and these systems carry a wide variety of additional features and ruggedized packaging that drive the cost well outside the range of feasibility. Lacking substantial growth of high accuracy non-instrumentation applications, there has been little or no market force to drive the development of higher accuracy low cost production devices.

Alternative GPS receivers using various types of carrier smoother code phase approaches combined with locally derived corrections (for example, using multiple frequency receivers) also offer the potential to provide high levels of accuracy, but, while initial research results are promising, it is unclear how well the systems will perform under dynamic motion situations (i.e. moving vehicles), it is unclear how quickly they will be able to resolve a high accuracy fix without a substantial initial dwell period, and it is unclear how they may be affected by multipath, especially in urban environments. It is possible that solutions to these issues can be found, but they will require additional research.

It is also necessary to more fully understand the implications of Automotive Safety Integrity Levels and how these may impact positioning requirements. Initial analysis of application failure rates indicates that the distributions of errors (i.e. the confidence) may need to be substantially tighter than the typical Gaussian error distributions observed with GPS systems. While the analyses developed on this project indicate reasonable positioning requirements in terms of allowable error radii, the ASIL analysis indicates that the “soft” edges of typical GPS error distributions may result in unacceptable application failure rates, at least relative to the ISO 26262 requirements.

It is probably also useful to develop a baseline ITS test regimen to assess these types of performance parameters in a consistent way, and to provide the development community a stable performance target to aim for.

Lastly, terrestrial GPS receivers do not provide any level of integrity monitoring. While reference station corrections include integrity measures for the corrections, the receivers themselves do not internally assess the integrity of the solution in the way that is required for aircraft systems. Such an enhancement is likely to be necessary for safety of life based systems.

1.2.2 RADAR Systems Findings

In general, RADAR is an effective relative positioning system for applications that do not require exceptionally high lateral position determination. While RADAR can exhibit high range accuracy, the spatial resolution is not ideal for applications requiring lane level lateral positioning. Radars with higher lateral acuity generally require larger antenna apertures and may also include expensive array or scanning systems. Wide bandwidth radars are emerging onto the market that can support a very narrow pulse, providing high range resolution and with matrix antennas that can support electronic scanning with good azimuth resolution. Ultra wideband (UWB) radar can provide a 3-D image because of its range resolution and ability to achieve good azimuth resolution. Processing of 3D USB radar is reasonably complex.

RADAR systems have the key advantage that they are independent, so they do not require, for example, that other vehicles be equipped with communications or positioning capability in order to determine the position of another vehicle and thereby allow an application to provide value to the user. This attribute is less useful; however, when the presence of the hazard is cannot be easily detected, and must be communicated, as, for example, with traffic signal information or MUTCD alerts and warnings. In these situations the absolute position of the vehicle must be determined, and then compared to the known (and communicated) location of the hazard. So, these systems, while excellent at providing position relative to other vehicles and measurable in-road hazards, are not useful for this other class of communicated hazard. Reflected radar signal strength vary with the materials with which the target is constructed, size of the target (radar cross section which can vary with aspect angle of the target), and geometry of the target which dictates the direction of the signal reflection. Stealth vehicles use this reflective geometry as well as radar signal absorbing material to reduce signal returns to levels that are essentially not detectable. As with all relative position sensors, blocking of the transmitted signal path (called masking) can cause an incomplete understanding of the target (vehicles and pedestrians) environment.

1.2.3 UWB Transponder Findings

Ultra wideband transponder positioning systems also fared quite well. They are capable of providing range measurements within a few cm accuracy. The design is reasonably simple and affordable in cost. Because a USB responder can only service one interrogator at a time, a protocol, such as Time Division Multiple Access (TDMA) must be incorporated. Time between range acquisitions can result in position error for a moving vehicle. Another issue with USB is the limited transmission power allowable by FCC and possibility of the ultra-wide band signal interference with other nearby communications devices. For this reason, ranging is limited to a few hundred meters.

1.2.4 Digital TV Ranging

Digital TV tower ranging was found to be totally inadequate relative to any of the applications. Latency and reference for ranging are technical issues. The methods available to improve these systems are inconsistent with the digital TV standards in the US, and are thus unlikely to ever be implemented in this country. The European digital mobile TV signal has a potential and test are being conducted in France. In addition, these systems require support from the TV station operators, and there does not appear to be any reason the operators would be motivated to do anything to support this opportunistic use of their signals.

1.2.5 LIDAR Systems Findings

LIDAR uses similar principals as RADAR. Short light pulses (around 5 nsec) are transmitted and two way time of flight used to determine range. A very narrow beam of light (sub-degree) is used to determine azimuth. LIDAR provides high accuracy relative positioning capability. Because the beam width is very narrow and easily controlled LIDAR exhibits substantially better lateral positioning capability than RADAR. Some lab grade (and very expensive) LIDAR systems can effectively generate a 3-dimensional “range image” of the road scene.

As with RADAR, LIDAR is an independent relative position measurement system, so it does not rely on other vehicles to provide their position, and the functionality of the system is not dependent on other systems outside its control. However, the system is problematic in applications that require absolute position, since in this situation the vehicle cannot generally discern its own position. It is possible, under specific circumstances to use LIDAR to determine absolute position using other sources of information. For example, if known reference reflectors are present, and the system knows the positions of the reflectors, then the LIDAR can determine the range to each reflector, and thereby determine its position relative to the reflectors, and subsequently, using the known positions of the reflector infer it absolute position. Such systems are relatively straightforward in controlled environments, but become increasingly complex as the environment becomes larger and more general. It may be possible, however, to locate reflectors of known cross section at, for example, an intersection, so that vehicles equipped with a LIDAR system could then calibrate their absolute position. Using this calibrated position, such a system might then use dead reckoning between such intersections.

There are two basic types of LIDAR: Scanning and FLASH. In scanning, the laser beam is mechanically moved across the horizontal field of view. In vehicle LIDAR, it is common to use multiple vertical beams (typically 4) that provide the vertical FOV coverage. The issue with scanning LIDAR is the revisit rate. This is based on the rate at which the beam is moved across the horizontal FOV (typically by a rotating mirror). FLISH LIDAR is a new technology that is very promising but currently expensive. It has no moving parts. It incorporates a wide angle laser that emits a signal and reflections from objects are received by a receiver matrix. An image grade return of the spatial coverage is achieved. Revisit rate is a function of the transmit pulse rate and is much higher than conventional LIDAR. Because it has no moving parts it is much better suited for vehicle applications. Current users are US DoD and NASA.

Vehicle Scanning LIDAR is designed to be mounted close to the surface and to provide a horizontal coverage of perhaps 120 deg. and a vertical coverage of perhaps 4 beams with 2 deg. separation (8 degrees V.). Infrastructure sensors are generally mounted on a pole or on the mast arm associated with the signal head. Thus the difference in viewing angles must be considered. For this reason, over the road, down looking, multi-beam LIDAR are offered by manufacturers for infrastructure use. FLASH LIDAR has good horizontal and vertical coverage and can accommodate both vehicle and infrastructure sensor applications. Like RADAR, LIDAR depends on target reflectivity; both materials characteristic (rough surface can defuse the signal) and color (some absorb signal wavelength) impact LIDAR reflection signal strength.

1.2.6 Video Systems Findings

Video sensing appears to also be a promising independent position sensing means. Current video sensing systems offer relatively good performance in limited situations. However, advances in video processing, driven by the animation and gaming industry, are rapidly improving this technology. It is likely that this will become the primary independent position sensing method (over RADAR and LIDAR) for ranges up to about 75 meters, during the next decade. Signal processing is reasonably intensive when considering target recognition and tracking capability. Recently a combined Video-RADAR sensor has been offered for infrastructure deployment with the radar providing range and azimuth accuracy and video providing target recognition and supporting reduction in probability of false alarm and improved probability of detection.

1.2.7 Other Findings

An unexpected observation from this study was that the applications that require relative positioning to other elements (usually to other vehicles) are better served by independent relative positioning systems such as RADAR and LIDAR. While some absolute positioning systems can support the accuracy requirements, the use of an absolute positioning system for these applications implies that the hazard vehicle (the one posing the risk to the host vehicle) communicate its position to the host vehicle. If this does not occur, the host vehicle has no information. This means that the availability of position information is not only dependent on the positioning system itself, but on the probability that the other vehicle is equipped. Given the very low rate of growth of features in production vehicles, coupled with the very large on-road fleet of non-equipped vehicles, the requirement that both vehicles in an encounter be equipped drives the effective availability of the positioning systems (the ability of the positioning systems to provide the position of the other vehicle) to nearly zero for many years. This can be seen in the analysis below that shows the growth rate of a feature in the U.S. vehicle fleet. This model uses a vehicle lifetime distribution with an average life of 13 years (so a few vehicles retire very early, a few last 25 year, and the average vehicle lasts 13 years). The model also assumes a nominal introduction of the feature (for example, an OBU capable of determining position and communicating it to another vehicle) that begins at zero installation rate, and grows in a typical "S-Curve" to 90% application rate over a 15 year period. This application rate is typical of non-mandated feature rates in motor vehicles. So, in year 1, some small percentage of the 15 million annual vehicle build is equipped, and after 15 years 90% of the annual build is equipped. Meanwhile, in year 1, there are 250 M vehicles on the road that are also not equipped. Each year about 15 M vehicles are retired. Most of these are around 11 to 15 years old (average of 13), but a few are very old, and a few are the newly equipped vehicles that were just built. Each year, some numbers of vehicles built in each previous year are retired, and some (rising) numbers of the new vehicles built are equipped. The application rate (annual percentage of new vehicles that are equipped) and the penetration rate (total percentage of vehicles on the road that are equipped) are shown as the blue line in Figure 1.2-1 below. The fleet penetration rate (red line) is essentially the probability that any given vehicle on the road will be equipped.

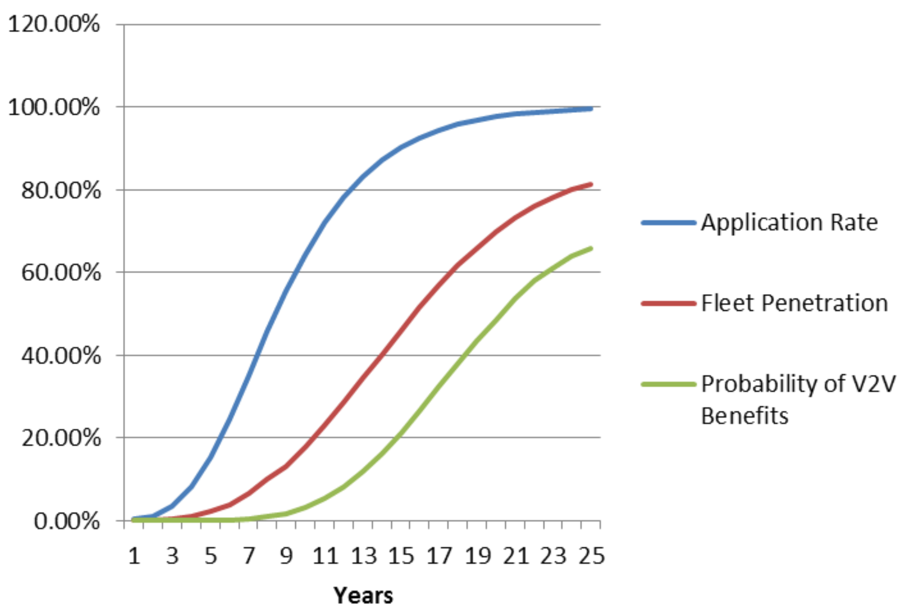


Figure 1.2-1 Application Rate and Penetration Rate By Year
Source: ARINC April 2012

Unfortunately, for two vehicles to share position information they must *both* be equipped, so the probability that a vehicle can share its position is found by squaring the penetration rate. This is shown in the green line in the figure above. As can be appreciated from the figure the probability that any two vehicles can share position information grows very slowly. This is effectively the availability for this relative positioning system 20 years after the introduction of the system, and 5 years after the annual production of vehicles with the new technology reaches 90%, the availability of the system for all vehicles on the road is still only 50 %.

This analysis was also carried out by Noblis using different application rates, and using a slightly more sophisticated model that analyzed miles driven instead of simple population (since newer vehicles tend to be driven more miles per year). The results from this analysis, provided in Figure 1.2-2 below, show that under normal consumer adoption rates ("High Consumer" in the figure), the availability of this positioning system 17 years after its introduction would be only 50%. If such a system were mandated, the growth rate would be faster and the 50% availability point would arrive 10 years after the initial introduction. The figure also indicates a still faster growth from a retrofit approach, but this is likely to be very expensive because of the multiplying factor (even if simple retrofit unit were to be sold for $X, and installed and tested for 2 ($X), the cost to retrofit 50% of the fleet would be (2X$) (125 mil) or $250X million (based on 250 million registered vehicles in the USA).

The rate of market penetration has many variables and is just a projection. Using historic data may not provide accurate because of changes in vehicle reliability, cost, economic conditions, which tend to extend vehicle ownership and useful life on corridors. The 2012 Edition of the "Human Machine Interface Report", by Telematics Update (telematicsupdate.com) [130], states: "It takes 12 years for new technology to make its way into a fleet of new cars." A University of California Berkley, Center for Entrepreneurship and Technology by Thomas Becker et al (August 2009) provides a detailed analysis of electric vehicle penetration into the market predicting a growth of 3% market penetration in 2010 to 64% of the private vehicle market in 2030. A Bosch study of Electronic Stability Controls (ESC) indicates that a mandate of implementation would only result in 55% of vehicles having ESC in 8 years. In an article entitled, "New Safety Techniques Takes Decades to Hit the Entire Market" by Colin Bird (In the News: Safety, Cars.com [120]), it is stated: "It typically takes three decades or longer for a new safety technology to spread to 95% of vehicles on the road, and it can take decades more for the technology to trickle down to the remaining 5% because of holdouts who love their vehicles too much to let them go, according to the Highway Loss Data Institute, an offshoot of the Insurance Institute for Highway Safety". The article points out that antilock brake systems which were introduced in 1985 will just reach 95% fleet penetration in 2015 (30 years). The projected time period for 100% of the fleet to be implemented with V2V/V2I safety technology as presented in this report is just representative, and illustrate the point that, due to the rate of vehicle implementation, (whatever number an analysis might show), infrastructure-based sensor systems will be required for a significant period of time. So, a relative positioning system that relies on the other vehicle to communicate its position will exhibit very low availability for many decades and consideration must be made for augmentation during the transition time.

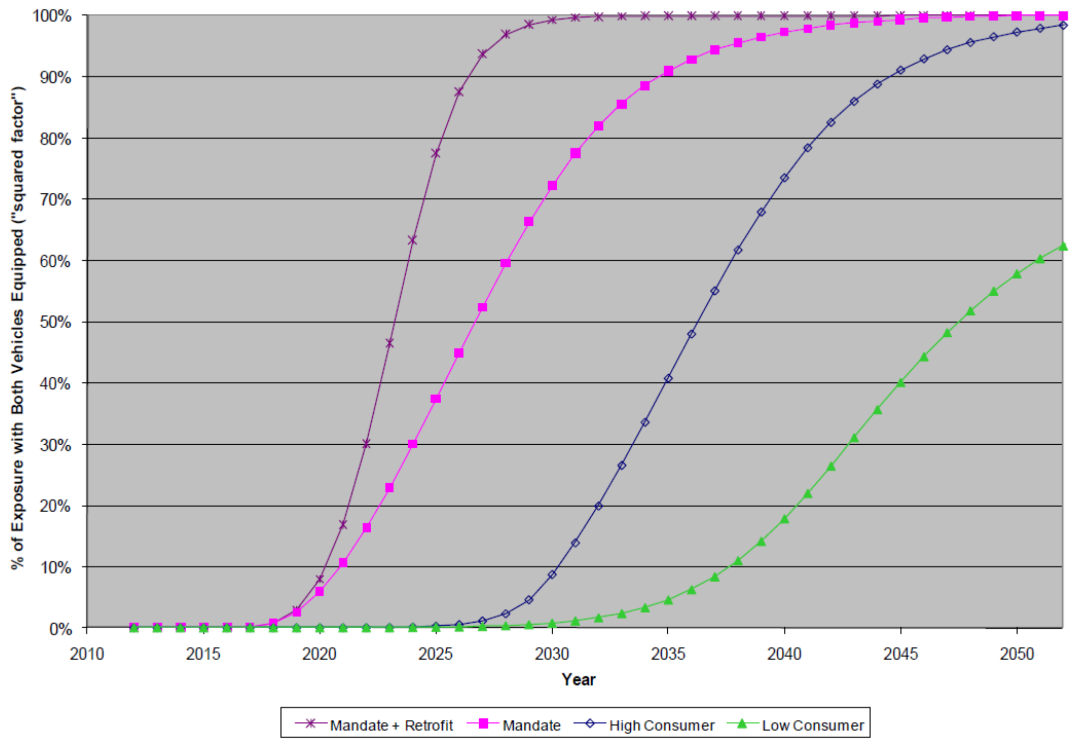


Figure 1.2-2 V2V Crash Exposure by Year

(Ref: Chang, J. (Noblis), "Market Penetration Analysis for VSC-A Safety Benefit Opportunities Estimation", Prepared under FHWA Contract #: DTFH61-05-D-00002, June 8, 2010 [103].)

Chapter 3 Target Application Requirements

To understand application requirements is it necessary to establish some nomenclature. Applications can be of two types:

Information applications provide information about the roadway that may be useful to the driver in either planning their trip or in carrying out the driving task. This information is most often provided in the form of an alert or warning message that is presented to the driver (e.g., “Road Closed ½ Mile”).

Control applications take some form of control action, such as steering the vehicle or applying the brakes, in order to avoid a collision or other safety related incident (e.g. automatically applying the brakes to avoid a collision).

In both types of application, the decision to act (present information in the case of an information application, or activate a control action in the case of a control application) is known as the “application event”.

1.3 Application Performance

In addition to correctly responding (either by taking action when it is required, or by not taking action when it is not required), the system can make two types of decision errors. These are known as false positives and false negatives. A false positive error occurs when the application decides to act and there is no reason to act. This is also known as a false alarm. Positioning related false positives typically involve the application acting too early or ahead of the preferred location of the application event point. The other type of error is a false negative, sometimes referred to as a missed detection. These errors are much more serious since they mean that the system has failed to act, or failed to act early enough, when a real hazard is present. In general, positioning related false negatives involve the system warning or acting after the preferred location of the application event, so there is insufficient time or distance for the driver to take appropriate action. Decision-making typically implies that one is deciding between two states, for example, is the user inside a specified geographic region (decision site), or outside a specified region? Because real world systems are based on measurements of reality, they are necessarily imperfect, and thus it is possible to make both correct and incorrect decisions. These are illustrated in Figure 1.3-1 below.

		Reality	
		Event Present	Event Not Present
Measurement	Event Present	True Positive	False Positive
	Event Not Present	False Negative	True Negative

Figure 1.3-1 Typical Decision Matrix
Source: ARINC April 2012

For example, in the figure above, the “event” might be “The vehicle is within X meters of the hazard”. The “response based on perception” is the decision that would result from a measurement of the vehicle position. The “proper response based on reality” is what decision would result from knowing the actual vehicle position. As shown in the figure, if the event is actually present, and the decision about the event based on perception is that it is present, the decision is correct. This is termed a “true positive” event because the event is present (Positive) and the decision based on perception is correct (True). If the event is not actually present, and the decision based on perception is also that the event is not present, and then this decision is correct. This is known as a “true negative” because the event is not actually present (Negative), and the decision based on perception is correct (True). The two error cases are also shown in the figure. If the event is not actually present, but the decision based on perception is that it is present, the decision is incorrect. This is known as a “False Positive” because the decision based on perception is that the event is present (Positive), but this decision is incorrect (False). Similarly, if the event is actually present, and the decision based on perception is that it is not present, this decision is incorrect. This is known as a “False Negative” since the decision is that the event is not present (Negative), and this is incorrect (False). Generally, false positives result in false alarms, while false negatives result in danger.

For each application, the relationship of the locations of false positive and false negative threshold relative to the ideal position of the application event forms the basis of determining the acceptable level of positioning error, and thereby defining the positioning requirements for that application.

1.4 Summary of Application Requirements

Table 1.4-1 below summarizes the positioning requirements developed in Section 3.4.

Table 1.4-1. Summary of Application Positioning Requirements

Application	Basic Positioning Requirements						Higher Order Position Related Parameter Requirements					
	Position (m)	Confidence (%) (Based on ASIL)	Location Reference Required?	Time Error (sec)	Integrity?	Availability Indication?	Logical Directionality?	Dimension	Velocity	Acceleration	Yaw	Slip
Hazards, Information, and Traffic Control												
MUTCD Related Alerts	6.7 m @ 60%	99.9	No	TBD	No	Yes	Yes	N/A	No	No	No	No
MUTCD Related Warnings	6.7 m @ 76.9%	99.99	No	TBD	Yes	Yes	Yes	No	Yes	May	May	May
Intersection Collision Avoidance - Traffic Signal Violation Warning	0.6 m Lateral 6.7 m Long @ 97.4%	99.9 99.999	Yes	TBD	No	Yes	Yes	Yes	Yes	Yes	No	No
Intersection Turn-Gap Assist	1.9 m Long	99.7%	<10 msec	TBD	Yes	Yes	Yes	Yes	May	May	May	May
Route Guidance and Dispatching												
Road Network Guidance	3.7 m Long	60%	Yes	N/A	No	No	N/A	N/A	No	No	No	No
Tolling, Clearing, Etc.												
Lane Gate Detection and Transactions	0.6 m Lateral 1.5 m Long	60%	Yes	<20 Msec	Yes	Yes	Yes	Yes	No	No	No	No
Traffic Management												
Probe Vehicle Data Collection (Collection of Vehicle Operating Data)	1.8 m Lateral (worst case) 25 m Long	60%	Yes	60 sec	No	No	N/A	N/A	Yes	No	No	May
Vehicle Safety and Security												
Lane Departure Warning	1.2 m lateral	60%	Y/N	>100 msec	Yes	Yes	Yes	Yes	Yes	Yes	Yes	May
Lane Change Warning	1.2 m lateral	76.9%	Y/N	>100 msec	Yes	Yes	Yes	Yes	Yes	Yes	Yes	May
Lane Guidance	1.2 m lateral	76.9%	Y/N	>100 msec	Yes	Yes	Yes	Yes	Yes	Yes	Yes	May
Automated Braking	0.3 m Lateral 2.75 m Long	99.7%	Y/N	<10 msec	Yes	Yes	N/A	Yes	Yes	Yes	Yes	Yes
Crossing Path V-V Warning	1.9 m Long	99.7%	Yes	>10 msec	Yes	Yes	Yes	Yes	Yes	Yes	May	May

Source: ARINC April 2012

1.5 Impact of Positioning System Errors

An ideal positioning system will report the exact position of the vehicle, so in this system the application event will be triggered when the reported vehicle position is at the application event location, and false positive and false negative application decisions will never occur. However, any real world positioning system will exhibit some level of positioning error. This error may be a result of physical position measurement inaccuracy, or it may be a result of secondary effects such as latency combined with vehicle motion.

1.5.1 Position Accuracy

Whatever the cause, a real positioning system can be characterized by an error region (typically a circle defined by an error radius) within which the actual position has some finite probability of occurring. This situation is illustrated in Figure 1.5-1 below. Here the ellipse shown represents the boundary of a confidence region wherein the probability that the actual position lies within the region is given by P. Typical positioning system accuracy specifications are thus typically provided in terms of the radius of the error circle (or radii of an ellipse) at a given level of confidence (i.e. the probability, P, that the actual position will be found within a circle of radius R).

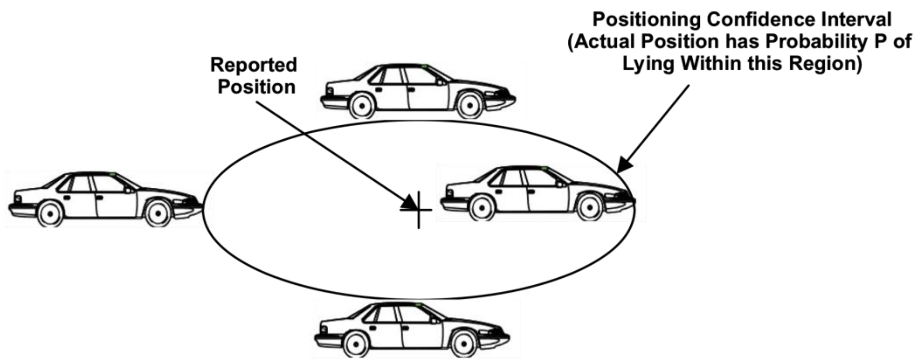


Figure 1.5-1. Example of Positioning Error and Confidence Region
Source: ARINC April 2012

When overlaid on the error diagram from Figure 3.3-1, as illustrated in Figure 1.5-2 below, the positioning accuracy problem becomes immediately obvious. Here we can see that the probability that the system will act too soon is 50% and the probability that it will act too late is also 50%. The probability that it will act correctly is vanishingly small. To overcome this problem, it is necessary to define a <u>region</u> within which the application should take action. This effectively divides the false positive and false negative regions into acceptable and unacceptable (or tolerable and in-tolerable) regions, and allows us to moves the unacceptable false positive and false negative regions away from the application event point. This allows for a practical system, since it can tolerate some level of error (the acceptable error regions), and the level of *tolerable* error can thus be used to develop positioning accuracy requirements. This is illustrated in Figure 1.5-2 below.

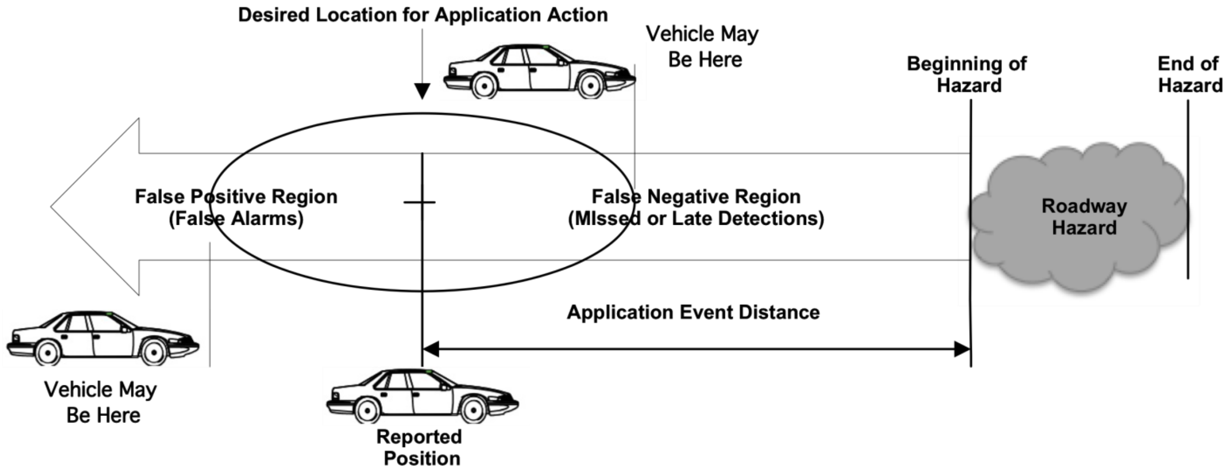


Figure 1.5-2. Application Decision Errors Caused By Positioning Error
Source: ARINC April 2012

The boundaries of this region are the closest and farthest points (or the earliest or latest points) at which the application event can occur and still meet the objectives of the application. To accomplish this, the application designer must determine the location that is too far from the hazard to be useful (i.e. the distance beyond which the application action would be perceived as too early, or too far from the hazard), and the location at which the application must take action or the system will fail to provide any safety benefit. For purposes of this discussion these points are called the false negative and false positive threshold points, and the region of acceptable false positive and false negative (and perfect) decisions is denoted as the application action region. These are illustrated in Figure 1.5-3 below.

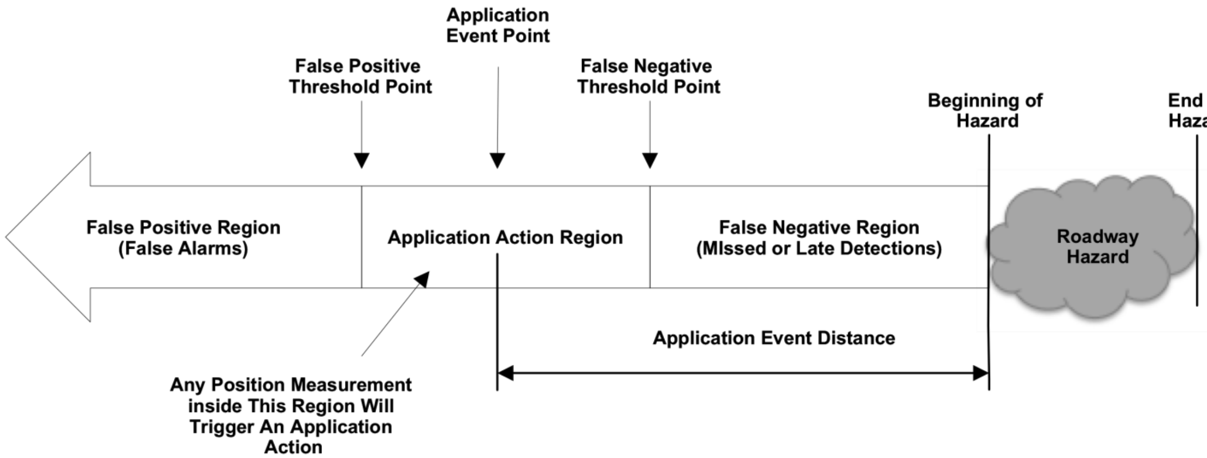


Figure 1.5-3. Development of the Application Action Region to Manage False Positive and False Negative Errors
Source: ARINC April 2012

Development of positioning system requirements is then a matter of determining the probability with which one can tolerate false positive or false negative application decisions. For example, if one must avoid false negatives and false positives with 90% confidence (i.e. 90% of the time), then one must impose a 90% confidence interval requirement on the positioning system. This is illustrated in Figure 1.5-4 below.

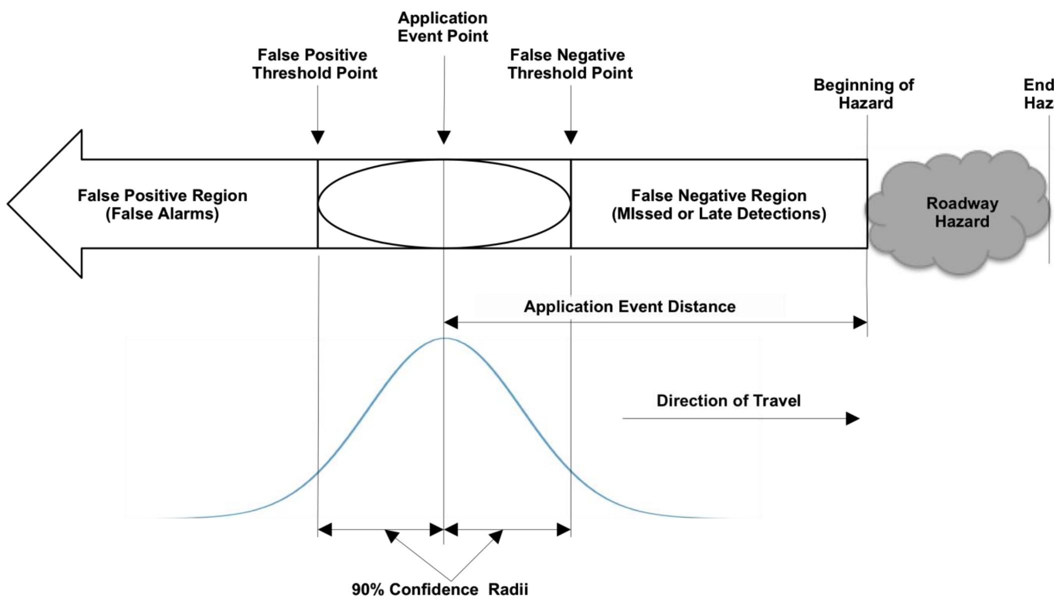


Figure 1.5-4. Superimposing Positioning System Distribution on Application Decision Regions
Source: ARINC April 2012

What this means is that when the positioning system reports that the vehicle position is at the application event point, there is a 90% probability that the actual position of the vehicle is inside the application event region (i.e. it is between the false positive and false negative thresholds).

In practice the requirements on false positive and false negative decisions may be different, so whichever requirement imposes the greatest limitation will be the one that must be used. The probability distribution is generally symmetric, so if, for example, the requirement is that false negatives must be avoided with 90% certainty and false positives can tolerate a 50% certainty, the system will perform to the higher 90% level for both types of decision error.

It is, however, possible to make use of differences in confidence levels for false positive and false negative decisions. For example, if one must avoid false negatives with 99% reliability, and false positives with, perhaps 75% reliability, then one can effectively shift the application decision point toward the false positive threshold. This has the effect of moving the position distribution farther from the false negative threshold, so the incidence of these errors will be reduced. This is illustrated in Figure 1.5-5 below.

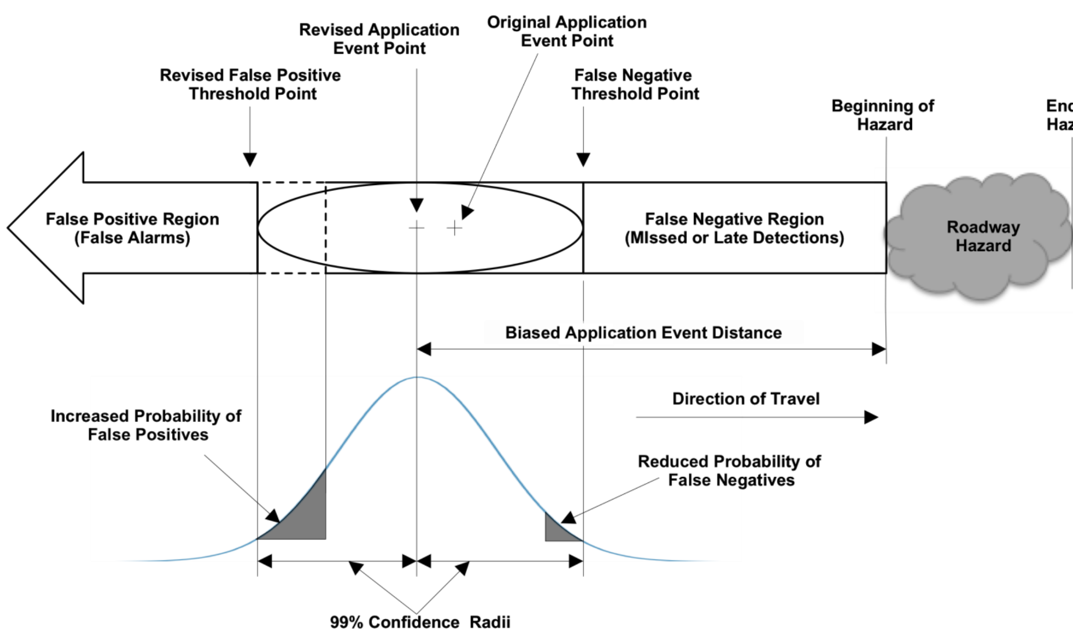


Figure 1.5-5. Shifting the Application Event Point to Reduce Probability of False Negatives
Source: ARINC April 2012

As can be seen in Figure 1.5-5, by shifting the application decision point toward the false positive threshold (but still within the application event region), the positioning system distribution can also be moved away from the false negative threshold. This has the effect of reducing the probability of this decision error. This shift is not, however, without impact. Because the probability distribution has moved toward the false positive threshold, this threshold must also move. Also, because the distribution is wider (to accommodate the increased confidence) the reduction in probability of false negative decisions produces a larger increase in the probability of false positives. As long as such an increase can be accepted, then this strategy allows the designer to fine tune the requirements to minimize the demand on the positioning system. Using the example above, the increase in confidence against false negatives from 90% to 99% may, for example, produce an increase in the probability of false positives from 10% (1-90%), to perhaps 20 or 30%. This is because the 9% increase in confidence against false negatives must be added to the probability of false positives, and the shift in the distribution effectively places the original false positive threshold deeper into the error distribution. This approach relies on the fact that, while the positioning system has a generally symmetrical error characteristic (errors in the direction of the event are just as likely as errors in the direction away from the event), the application may have a greater tolerance for false alarms than for missed detections. So, the designer can essentially increase the likelihood of false alarms, while decreasing the likelihood of missed detection, using the same accuracy positioning system.

The application requirements depend entirely on the application geometry and the acceptability (or not) of false positive and false negative errors. The process described above can then be used to determine what sort of position error distribution can be tolerated within the boundaries of the application. This then becomes the positioning system requirement.

This approach, however, has one additional complexity. Positioning systems are generally specified in terms of a static distribution of position estimates. Typically the system is placed at a known position, and a distribution of position estimates is collected. The statistical parameters of this distribution are then used to characterize the accuracy of the system. For example, as described above, one might quote a 90% confidence interval radius of 5 meters for a system. This means that any reported position has a 90% probability of being within 5 meters of the actual position. Unfortunately, in practice one does not have the luxury of dwelling at a particular point so as to collect a distribution of position estimates. Typically, in fact, the positioning system is on a moving vehicle, and it produces only a single position estimate. This estimate is effectively a sample of the distribution at that particular location. The problem is that one has no idea where in the distribution this sample may be. According to the specification of the positioning system, it has a specified probability of being within some specified distance of the actual position, but one cannot know from the sample in which direction the mean value of the distribution (implicitly the actual position of the vehicle) lies. A common mistake is to assume that the positioning system distribution is centered on the reported point. However, this is incorrect, because the distribution must be centered on the actual position. The measured point is simply one of the samples that, if the positioning system static, would accumulate around the actual position to form the distribution. This issue is illustrated in Figure 1.5-6 below.

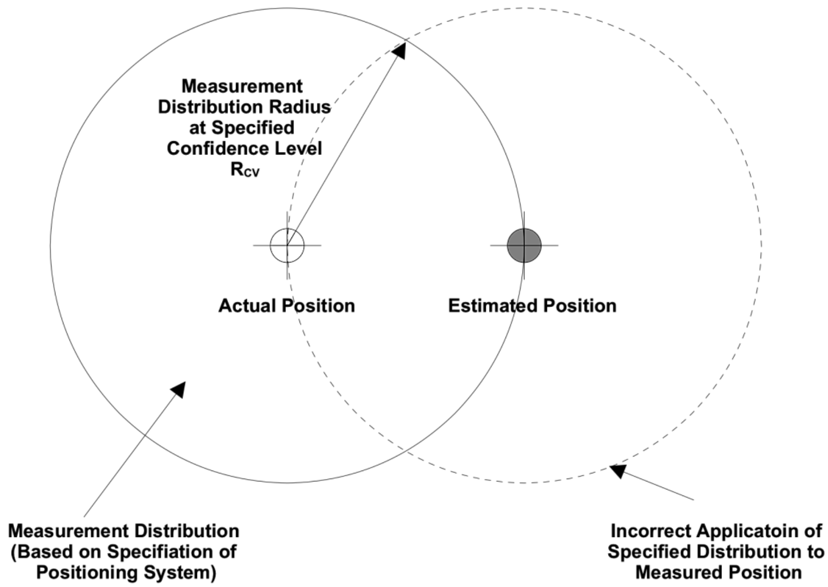


Figure 1.5-6. Interpretation of Single Measurement Estimate
Source: ARINC April 2012

Since, for a moving vehicle, there is only one estimated position at each location, there is no way to properly interpret the meaning of the estimated position. The result will be one or the other type of application decision error. If the estimated position is off from the actual position in the direction of travel of the vehicle, then the application will falsely decide to act at twice the distribution radius. This is illustrated in Figure 1.5-7 below.

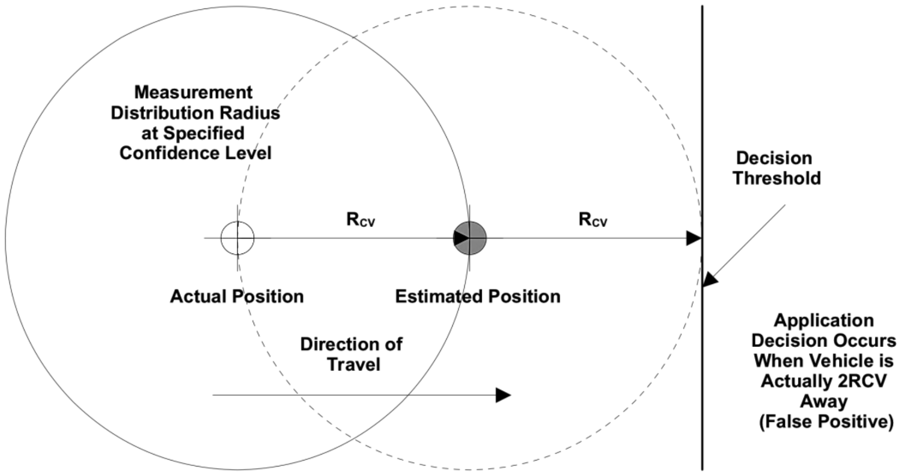


Figure 1.5-7. False Positive Decision Resulting From Single Position Measurement
Source: ARINC April 2012

If, on the other hand, the position estimate is off in the direction opposite the direction of travel, then the application will act when the vehicle is right at the decision point (instead of one radius away from it. This situation is illustrated in Figure 1.5-8 below.

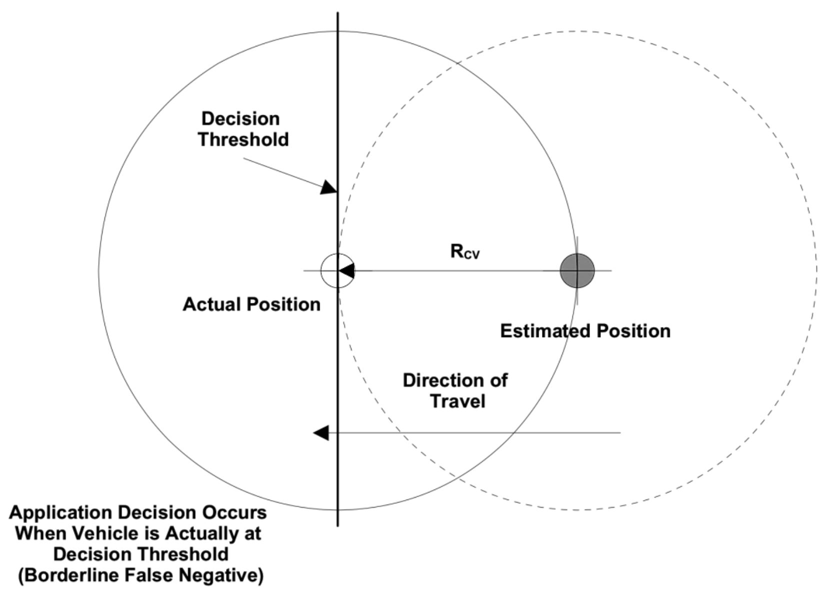


Figure 1.5-8. Borderline False Negative Decision Resulting From Single Position Measurement
Source: ARINC April 2012

This situation is not necessarily bad, since the application will still act in time to avoid a false alarm within the specified confidence level; however, since this phenomenon is biased in favor of false positive errors, it does explain the high level of false alarms typically experienced in position based warning systems. One way, of course to reduce the effect of this problem is to increase the accuracy requirement on the positioning system. A dynamic system will exhibit the same false alarm rate as a static system with half the accuracy of the dynamic system.

1.5.2 Position Reliability, Safety, Sensor Integrity and Confidence Level of Sensor Position

The generally accepted approach for defining safety level requirements is the Safety Integrity Level or SIL. SILs are measures of the safety risk of a given process, and essentially define to what extent can a process be expected to perform safely? And, in the event of a failure, to what extent can the process be expected to fail safely? This process is described in the IEC 61508 standard. More recently the concept of Automotive SIL has been developed and is specified in ISO 26262.

Under the ASIL approach, safety is stratified into five discrete levels: QM, A, B, C and D, with D being the highest level of safety required. Each level represents an order of magnitude of risk reduction.

The ASIL for an application, or a system that implements an application, is based on three core factors: Severity, Exposure and Controllability.

- Severity is a measure of the potential for injury, and the severity of those possible injuries, should a fault occur.
- Exposure is a measure of how frequently the system may be experience a situation in which the fault is relevant (i.e. a hazardous event).
- Controllability is a measure of the probability that the driver or other endangered persons are able to gain control of the hazardous event, and are able to avoid harm.

These factors are combined as shown in Figure 1.5-9 below to determine the ASIL for the specific situation under consideration.

		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

Figure 1.5-9. ASIL Levels
(Ref: "ISO 26262 for Safety-Related Automotive E/E Development - Introduction and Concept Phase",
Michael Soden; June 2011)

Proper assessment of these (S, E & C) factors requires that a detailed hazard analysis be carried out based on how the application would react to a failure. These are described in Table 1.5-1 below.

Table 1.5-1 ASIL Parameters

Measure		Metric	Example
Severity			
S0	No Injuries	AIS* 0	Rear Collision at ΔV<10 kph
S1	Light and Moderate Injuries	>10% Probability of AIS 1-6 (and Not S2 or S3)	Rear Collision at ΔV<20 kph;
S2	Severe Injuries, and Life-Threatening Injuries (Survival Probable)	>10% Probability of AIS 3-6 (and Not S3)	• Rear Collision at ΔV<20-40 kph; • Urban Ped/Cyclist Collision
S3	Life-Threatening Injuries (Survival Uncertain), and Fatal Injuries	>10% Probability of AIS 5-6	• Rear Collision at ΔV>40 kph; • Suburban Ped/Cyclist Collision
Exposure			
E0	Incredible (Force Majeure)	<0.01% of Operating Time	Flash Flood, Meteorite
E1	Very Low Probability	<0.1% of Operating Time Situations that occur less than once a year for the great majority of drivers	• Stop at railway crossing, which requires the engine to be restarted • Jump start
E2	Low Probability	<1% of Operating Time Situations that occur a few times a year for the great majority of drivers	• Driving on a • mountain pass • with an unsecured • steep slope • Driving situation • with deviation • from desired path
E3	Medium Probability	<10% of Operating Time Situations that occur once a month or more often for an average driver	• Fuelling • Overtaking • Tunnels • Hill hold • Car wash • Wet roads • Congestion
E4	High Probability	>10% to Always All situations that occur during almost every drive on average	• Starting • Shifting gears • Accelerating • Braking • Steering • Using indicators • Parking
Controllability			
C0	Generally controllable	Generally possible to control	• Unexpected increase in radio volume • Situations that are considered distracting
C1	Simply controllable	99% or more drivers and other participants can avoid harm	When starting the vehicle with a locked steering column, the car can be brought to stop by almost all drivers early enough to avoid a specific harm to persons nearby
C2	Normally controllable	90% or more drivers and other participants can avoid harm	Driver can normally avoid departing from the lane in case of a failure of ABS during emergency braking
C3	Difficult or uncontrollable	Less than 90% of drivers and other participants can avoid harm	Driver normally cannot bring the vehicle to a stop if a total loss of braking performance occurs

Source: ARINC April 2012

For most connected ITS applications, the exposure rate is greater than 10% of the time (e.g., braking, turning, etc.), so this would make the typical exposure level E4. Similarly, for non-automated applications, the controllability is generally greater than 99% (C1). This is because the driver is assumed to be in control, and the system is simply providing added safety benefits. For automated control applications, such as automatic braking, the controllability is likely to be less than 90% (C3) since the driver is not in control, and if the system fails it is probably too late for the driver to react properly.

Table 1.5-2 below provides the ASIL as a function of degree of automation and severity. These attributes are more directly relatable to the various ITS applications described in this report.

The reliability (confidence) levels included in the table are based on a 5,000 hour usage life for a vehicle. This is nominally 150K miles at an average speed of 30 mph, or a 5% duty cycle over a 12 year average life span using the well-known reliability formula:

$$\text{Reliability} = e^{-\lambda T}$$

Table 1.5-2 ASIL Levels by Application Type

		Type of Application	
Severity		Non-Automated (e.g., Warning)	Automated (e.g., Steering/Braking)
S0	No Injuries	ASIL QM (not safety critical) PDF< 10^{-4} Conf.=59.1%	ASIL A PDF=10^{-6} to 10^{-5} Conf=97.4%
S1	Light and Moderate Injuries	ASIL QM+ PDF=10^{-5} to 10^{-4} Conf.=76.9%	ASIL B PDF=10^{-7} to 10^{-6} Conf.=99.7%
S2	Severe Injuries, and Life-Threatening Injuries (Survival Probable)	ASIL A PDF=10^{-6} to 10^{-5} Conf.=97.4%	ASIL C PDF=10^{-8} to 10^{-7} Conf.-99.97%
S3	Life-Threatening Injuries (Survival Uncertain), and Fatal Injuries	ASIL B PDF=10^{-7} to 10^{-6} Conf.=99.7%	ASIL D PDF<10^{-8} Conf.=99.997%

Source: ARINC April 2012

Determining the allowable error and from the ASIL is complex. This is because different levels of error relative to the application requirement are likely to have substantially different consequences. For example, a Red Light Running application (where the application determines the signal phase and timing and warns the driver if they should stop), the nominal application position requirements are determined by the difference between a point where the warning would be perceived as too soon (false alarm) and the point where the driver would need to brake at an emergency level in order to stop at the limit line. This application has an allowable error radius of 6.7 meters. However, if the position error is just slightly larger than this, the likelihood of injury is not substantially higher. For example, if the error is ½ car length larger than this requirement, the consequence is only slightly higher risk of an accident since at maximum braking, the car would nose out into the intersection. If the error is 2 car lengths larger, then, in the false negative case, an accident is likely, and injuries may occur, since the vehicle would effectively block an entire lane in the intersection by the time it stopped. So, for this application, the allowable failure rate between 2.75 meters and 4.6 meters would be less than 10^{-4} (ASIL QM), while for the failure rate for an error between 4.6 meters and 9.2 meters would be between 10^{-6} and 10^{-5} (ASIL A)

On the other hand, if the application is a V2V collision avoidance braking system, then, assuming the vehicle would normally stop ½ car length (4.6 meters away from the car ahead, an error of 2.75 meters will result in the vehicle stopping right at the bumper of the lead vehicle. Errors greater than this will result in collisions at speeds that will increase as the distance error increases. For example, if the vehicle is braking from 40 Kph toward a stopped car, and the vehicle stops 2.75 meters past the bumper of the stopped car (double the allowable error), the contact speed will be 6.3 meters per second, or 22 kph. This places the injury severity index at S2 (severe but survivable injuries), and the ASIL value would be ASIL C (PDF=10^{-8} to 10^{-7})

Developing this relationship between positioning error specifications (error radius and confidence interval) and the failure of the resulting application to perform properly within the failure rates associated with the ASIL value is a key research topic that should be examined in greater detail. Figure 1.5-10 below illustrates the conceptual relationship between ASIL derived reliability requirements and positioning errors. Essentially, the allowable failure rate (or required reliability or confidence) for each ASIL level, coupled with the degree of severity associated with successive levels of position error can be used to define an error distribution template for each application. This can then be used to define a required error radius at a specified confidence level. Any usable positioning system must have errors that fall within the distribution template.

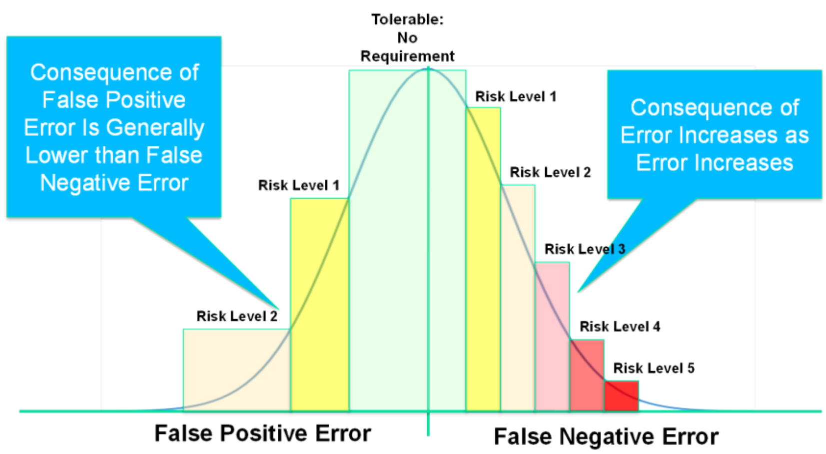


Figure 1.5-10 Relationship between ASIL Values and Positioning Requirements
Source: ARINC April 2012

In a similar manner that FAA specifies performance and reliability of sensors as well as quality assurance and testing, this will also be required for surface vehicle sensors that are used to support applications associated with safety of life. The Failure rate (FR) of components and the design architecture are used to develop the failure rate and mean time between failure (MTBF) for the sensor equipment (MTBF = 1/ (failure rate)/ (time period)). Mean time to repair (MTTR) is the time that it takes to restore the failed system to its normal operational performance and includes replacement, test and calibration time. Using field or shop replacement at the "black box" level, MTTR applies to unit replacements, test and calibration and not to circuit board or component replacement, test and unit calibration. Availability of the sensor, in reliability terms, is:

Availability (A) = MTBF/ (MTBF + MTTR)

Reliability over a specific time period (R_t) is determined by:

$$R_t = e^{-\lambda t};$$

A typical failure rate (λ) for a sensor is 0.00001 failures per hour, thus R_t for a commercial vehicle trip of 48 hours would be:

$$R_t = e^{-(0.00001)\,(24)} = 0.999.$$

This means that there is a 0.999 probability that the sensor will perform to specification during the 48 hour trip time. The MTBF for the sensor would be one failure in 90,000 hours. If it required 1 day of shop time to replace, test and calibrate a failed sensor, the Availability of the sensor would be 90,000/ (90,000 + 24) = 0.9997 availability. Thus the sensor has a 99.97% probability of being available.

Where fault tolerant design is utilized (one back up), the fault tolerant Availability (A_{FT}) is:

$A_{FT} = 1 - (1 - A)^2$, where A is the Availability of a single unit.

Integrity is the ability of a sensor to provide a position within its specification in terms of error radius and confidence (probability that the position provided is within the error radius).

In general, determining integrity requires both multiple coincident measurements and the subsequent determination of the variance between these measurements, or it requires a cross-check of a measurement using a different type of sensor. Absolute positioning systems like GPS can assess integrity by making multiple coincident (simultaneous) position measurements, and then determining how widely separated these measurements are. For example, the Receiver Autonomous Integrity Monitoring (RAIM) system required by the FAA uses the multiple position fixes available when five or more GPS satellites are available.

For relative positioning sensors such as RADAR or LIDAR, it is difficult to obtain Integrity for the measured location of a safety related target because there is no convenient way to cross-check the measurement. It is possible to determine the quality of the return signal in terms of signal to noise level (which is a function of target range and reflectivity or cross-section in the case of RADAR and LIDAR). But this approach does not generally validate the ranging measurement as much as it validates the existence of the target.

Confidence level in the target location can be enhanced by:

- Correlating the measured position with a predicted position provided by a tracking system, such as a Kalman filter;
- Correlating the measured position with positions reported by other sensors; this is typically referred to as sensor fusion.

One major concern with sensor fusion approaches is latency in the various sensors, target trackers and fusion processors and its impact on position error as the vehicle continues to move. Furthermore, differences in accuracy for the different sensors must also be taken into account. Differences in latency between various signal processing, tracking and fusion algorithms used by different manufacturers will impact performance from one car to another (assuming they use different manufacturers and sensor/sensor processing designs). For this reason standards must be developed that specify acceptable accuracy and latency.

Some of the available relative positioning sensors have built in calibration and test features. A detailed analysis of these built in test and calibration features would be necessary to evaluate their effectiveness to determine performance failures. Where real time, built in test features are included with the sensor, an applications processor to manage the performance of OBE and manage failure reporting and inhibited use of information from a failed sensor, tracker and/or fusion processor. Corrupted data, caused by a failure should be prohibited from being propagated through the OBE subsystems and communicated to other vehicles and RSE.

There is a challenge to manage all of the evolutionary configuration updates considering the variations in sensor suites that may be deployed, even within one manufacturer's model of a vehicle. Software upgrades must be backward compatible with hardware and supporting operating system and utilities. Software upgrades may also impact calibration and testing of sensor related equipment. This again will be a challenge to vehicle and vehicle equipment configuration management.

A paper entitled, "As Electronics Expand, So Do Challenges Facing Automobile Designers" (*Automotive News*, 9-29-2010 [121]) illustrates some of the issues associated with maintenance, based on design. The article states: *"The major challenge facing automotive electronics designers is the high degree of connectivity required within the vehicle. In just the past decade, the magnitude and complexity of the interconnection of automotive electronics has increased dramatically. Depending on the vehicle, there can be 3 to 15 ECUs* [Electronic Control Units] *(over 50 in some high-end vehicles) with hundreds of embedded software modules; and each of these applications must inter-communicate. Adding to the complexity is that each ECU presents its own challenge, given that the software, middleware and application software is written by different companies, yet must be integrated together within the overall framework of the vehicle."* The paper also indicates the management complexity associated with advanced, distributed automotive systems since tier 1 and tier 2 suppliers are responsible for design and testing.

Another technical report entitled, "Challenges in Automotive Software Engineering", by Manfred Broy (*Proceedings of the 28th International Conference on Software Engineering*, 2006 [122]), emphasizes some of the maintenance challenges. The paper states that in the first three years of production of an advanced vehicle, 20% to 30% of the ECUs must be replaced with different versions because problems have been detected and/or improvements have been made. The issue is software compatibility of ECUs over the complete, distributed, vehicular system. Many of these ECUs are tightly coupled and even changes in latency cannot be tolerated. The report further discusses the growth in information multiplexing on an increasing number of vehicle data busses and the challenges of managing the protocol evolution. The report stresses the fact that vehicle designs are getting more complex and both design and diagnostic skills must evolve to meet the challenges of advanced vehicles.

1.6 Development of Positioning Requirements for Selected Applications

To develop specific requirements for the selected applications we must determine the minimum response distance and the maximum response distance. The minimum response distance represents the false negative threshold. The assumption is that if the application does not act prior to this point, it will fail to provide its intended benefit. For example, if the intended benefit of the application is to prevent stopping past a stop sign limit line, then the minimum response distance is the distance at which the driver can react, and stop the vehicle right at the limit line under maximum assumed longitudinal acceleration. The maximum response distance represents the false positive threshold. The assumption is that if the application acts prior to this point, the driver will perceive the application as over-reacting and producing false alarms. Using the same example above, if the intended benefit of the application is to prevent stopping past a stop sign limit line, then the typical response distance is the distance at which the driver can react, and stop the vehicle right at the limit line under typical assumed longitudinal acceleration and with typical assumed reaction times. The typical application response times will in most cases be quite similar to the Perception Response Distances described in the Manual of Uniform Traffic Control Devices (MUTCD). In general, it may be advisable to assume a slightly shorter driver reaction time so that the system does not react at the same time as the driver. This allows the application to determine if the driver is reacting and thereby suspend or modify the application action to avoid interfering with normal driver behavior. Essentially, if the driver fails to react at the expected time, then the application will take action. If the driver does react at the expected time then the application may do nothing (depending on the implementation). The detailed development of requirements for warning applications thus depends on various human factors elements. In the following analyses we have used perception and sight distances as described in the MUTCD for the nominal performance, and used high and low versions of these (for example, ±30%) to set the false positive and negative thresholds. These values seem reasonable, but they should be examined, and may be refined by a more formal human factors analysis.

The following sections define the positioning requirements in terms of these distances for key groups of applications that share similar responses. These tables and the accompanying descriptions are based on a systematic process that is described in a detailed example in Appendix D.

1.6.1 MUTCD Related Alerts

Alerts are intended to inform the driver about upcoming road situations, but are generally not intended to invoke any sort of immediate response.

As a result, the position at which the alert is to be provided is not critical as long as it is sufficiently far in advance of the condition that the driver can understand the intent of the alert and prepare accordingly. Table 1.6-1 below provides distances traveled over various perception times at various speeds. The typical perception time of 1.5 seconds is shown in bold.

Table 1.6-1. Perception Time and Reaction Distances versus Speed

Speed (MPH)				
Perception Time (Sec)	**30 (48.2 km/hr)**	**45 (72.4 km/hr)**	**60 (96.6 km/hr)**	**75 (120.7 km/hr)**
1.00	44	66	88	110
1.25	55	83	110	138
1.50	**66**	**99**	**132**	**165**
1.75	77	116	154	193
2.00	88	132	176	220
Reaction Distances (ft)				
False Positive	88	132	176	220
Typical	66	99	132	165
False Negative	44	66	88	75
Distance Between False Positive and False Negative Points				
Feet	44	66	88	110
Meter	13.4	20.1	26.8	33.5

Source: ARINC April 2012

Position measurement errors in this application will show up as early or late alert presentation, so an alert presented at the 2 second limit would be seen as a false positive (early alert), while an alert presented at the 1 second limit would be seen as a false negative (late alert)

As can be appreciated from the table, at 30 mph (48.3 km/hr), the distance difference between the false negative point and the false positive point is 44 feet (13.4m), or a position error radius of about 22 feet (6.7 meters). At higher speeds these differences grow substantially, implying a greater tolerance for positioning errors at higher speeds. As a result it is reasonable to assume for MUTDC alerts that the position accuracy requirement should be about 20 feet (6.1 meters) radius. Non-automated alerts may be safety related, but the risk of fatalities is generally very low, it is assumed that the ASIL for this application is level QM with a corresponding confidence level of 60%.

1.6.2 MUTCD Related Warnings

MUTCD related warnings are intended to cause the driver to take some form of action. This is especially true for in-vehicle warnings that are triggered by vehicle speed. Normal MUTCD warning signs are placed at the decision sight distance for the 85th percentile speed on the road segment. Some warnings simply require a driver to take some form of simple corrective action, for example, change lanes at a lane shift. A more critical warning is where the vehicle must be brought to a stop. For example, a typical MUTCD application might be a warning light around a curve from an obscured traffic signal. In this case the light would flash when the signal was red. As above, the mean perception time is assumed to be 1.5 seconds. We have assumed that, since this is a warning application that there is a corresponding alert application, so the driver is already aware of the situation. As a result we are using Stopping Sight Distances, not Decision Sight Distances. (See AASHTO *2001 Greenbook* for definitions of Decision and Stopping Sight Distances).

Table 3.4-2 below illustrates the response distances for these typical values and for emergency values.

Table 1.6-2. Perception and Stopping Distance versus Speed

		Speed (mph)			
		30	**45**	**60**	**75**
Perception Reaction Time (Sec)	1.00	44.1	66.2	88.2	110.3
	1.50	66.2	99.2	132.3	165.4
	2.00	88.2	132.3	176.4	220.5
	2.50	110.3	165.4	220.5	275.6
Deceleration Level (g)	0.34	88.2	198.5	352.9	551.5
	0.51	58.8	132.4	235.3	367.6
	0.68	44.1	99.3	176.5	275.7
False Positive Distance		176.4	330.8	529.3	772.0
Nominal Distance		125.0	231.6	367.6	533.0
False Negative Distance		88.2	165.4	264.7	386.0
Distance Between False	Feet	88.2	165.4	264.7	386.0

Positive and False Negative Points	Meters	26.9	50.4	80.7	117.7
Required Accuracy Radius	Feet	44.1	82.7	132.3	193.0
	Meters	13.4	25.2	40.3	58.8

Source: ARINC April 2012

This table indicates that for MUTCD alerts, the false positive point (2 second perception distance, nominal braking level) is at 176 feet for 30 mph. Similarly, the false negative distance (1 second perception time, maximum braking) is 88 feet. As can be seen in the table, the distance between the false positive and false negative points is about 88 feet (26 meters). So the minimum error radius for these applications is about 22 feet (6.7 meters). Non automated warnings are safety related, but the risk of fatalities is generally quite low, it is assumed that the ASIL for this application is level QM+ with a corresponding confidence level of 76.9%%.

Depending on the application, and the severity of the consequences of a failure, the positioning system may require a measure of integrity or an indication that the system is otherwise unavailable. Generally higher order positioning parameters are not required other than directionality (is the vehicle traveling in the direction of the hazard?) and velocity.

1.6.3 Intersection Violation Warnings

Intersections require a special type of warning where the state of the warning changes over time. Because the vehicle may be at any distance when the signal changes, the determination of the worst-case situation is required. One situation arises when the signal changes from green to yellow when vehicle is located at the point where the driver must perceive the change in signal state, activate the brake, and bring the vehicle to a stop at the intersection limit line. Depending on the situation, the driver may be put into a dilemma: Is it too late to stop safely, or is it too late to avoid entering the intersection on the red phase of the signal? We are not seeking here to resolve this dilemma directly. Generally, the intersection warning distances are the same as for MUTCD related warnings (here the hazard is simply the limit line). The key difference between intersection warnings and MUTCD warnings is that the signal timing will cause these warnings to change, and the determination of whether the warning is issued is more complex because of this timing. The accuracy requirements, however, are not any different. The lateral error is the same as the lane gate discussion elsewhere in this report.

Non automated warnings are safety related, but the risk of fatalities is generally low. However, intersection signal violations pose generally greater risk than, for example, a roadway obstacle due to the higher probability of a collision as shown by intersection accident statistics. So, it is assumed that the ASIL for this application is level A with a corresponding confidence level of 97.4%.

It is also instructive to examine the impact that deceleration level has on this requirement. In Table 3.4-2 above, we have assumed that in an emergency situation the driver would brake at about the ABS limit (assumed here at 0.68g). If the braking action is at the nominal level of 0.34 g (as typically used in traffic planning), the difference between the false positive distance and the false negative distance is much smaller, and the positioning accuracy requirement is much tighter. This is shown in Table 3.4-3 below where we have assumed that all braking (false positive and false negative situations) is done at 0.34 g.

Table 1.6-3. Perception and Stopping Distance versus Speed

		Speed (mph)			
		30	**45**	**60**	**75**
Perception Reaction Time (Sec)	1.00	44.1	66.2	88.2	110.3
	1.50	66.2	99.2	132.3	165.4
	2.00	88.2	132.3	176.4	220.5
	2.50	110.3	165.4	220.5	275.6
Deceleration Level (g)	0.34	88.2	198.5	352.9	551.5
	0.34	87.0	195.7	347.8	543.5
	0.34	88.2	198.5	352.9	551.5
False Positive Distance		176.4	330.8	529.3	772.0
Nominal Distance		153.1	294.9	480.1	708.9
False Negative Distance		132.3	264.7	441.1	661.7
Distance Between False Positive and False Negative Points	Feet	44.1	66.2	88.2	110.3
	Meters	13.4	20.2	26.9	33.6
Required Accuracy Radius	Feet	22.1	33.1	44.1	55.1
	Meters	6.7	10.1	13.4	16.8

Source: ARINC April 2012

Using the same braking level of 0.34 g, the distance between the false positive and false negative points drops to 44 feet (13.4 meters), which implies a positioning error radius of 22 feet (6.7 meters).

It is unclear if the high braking level of 0.68 g can be realistically assumed in all cases, but it does appear that assuming that the driver will stop at a nominal leisurely rate in an emergency warning situation is also unrealistic. (Note that there is also the higher probability of a rear end collision with higher deceleration rates).

A slightly different situation occurs when the signal changes from yellow to red. Here the driver should have been aware that the light was yellow, and he should be prepared for the change to the red phase. His safe course of action is to brake to a stop at the intersection limit line. (However some researchers, such as that documented in the paper entitled, “Investigating the Effects of an Advanced Warning In-Vehicle System on Behavior and Attention in Controlled Driving (*Proceedings of the 3rd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2011 [123]), suggest that advanced warning has only a limited effect on driver behavior). Analysis indicates that the positioning accuracy requirements in this situation are not substantively different for the above (yellow phase) case.

1.6.4 Intersection Left Turn Gap Assistance

The intersection left turn gap assistance application involves determining the relative distance and speed of an oncoming vehicle when the equipped vehicle is planning to turn left across the path of the oncoming vehicle, and warning the host vehicle driver if the gap is insufficient to make the turn.

To properly determine if a hazard exists, the time to reach the intersection, and execute the turn must be less than the time before the oncoming vehicle enters the intersection. If the timing is insufficient to complete the turn before the oncoming vehicle arrives at the intersection, then the host vehicle must stop.

The basic physical situation and the variables associated with the problem are shown in Figure 1.6-1 below. Here the system should decide to warn if the time for Vehicle A to reach the intersection and to execute the turn (T_A+T_T) is less than the time required for Vehicle B to reach and enter the intersection (T_B). If this is the case, then Vehicle A will still be in the intersection when Vehicle B enters it. The other warning situation is if the time for Vehicle B to reach the intersection and cross it (T_B+T_I) is less than T_A, the time for Vehicle A to reach and enter the intersection. If this is the case, then Vehicle A will enter the intersection before Vehicle B has cleared it. Obviously, if the correct action is for Vehicle A to stop, then the warning to do so should be provided early enough that Vehicle A can in fact stop prior to entering the intersection, and the time required to execute the turn will depend on the speed of Vehicle A and the radius of the turn.

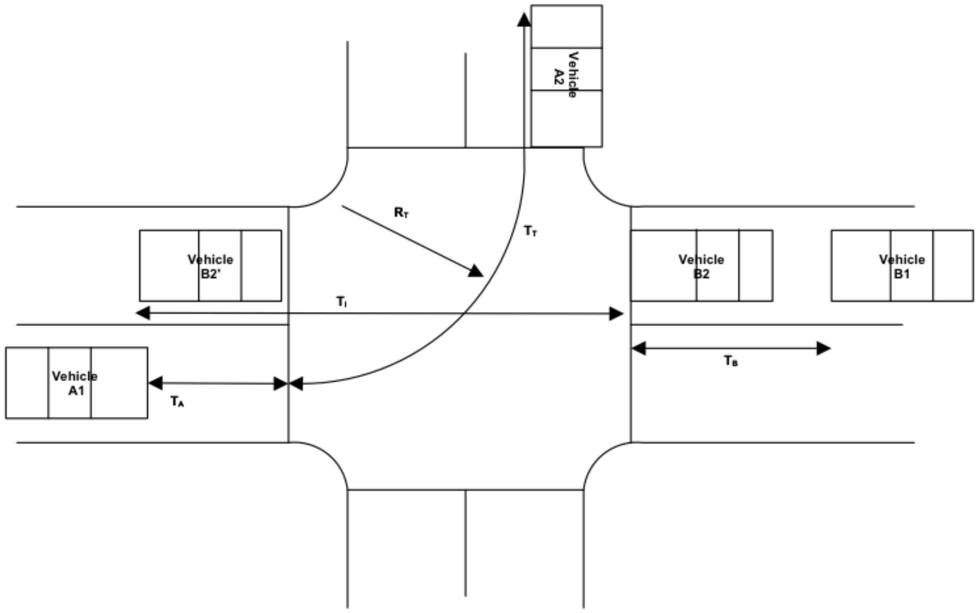


Figure 1.6-1. Intersection Left Turn Gap Assistance Physical Setup
Source: ARINC April 2012

Generally, to maintain a nominal lateral acceleration level, the typical speed through the intersection turn is about 12 mph. The geometry and timing for turning through several intersection types is provided in Table 3.4-4.

Table 1.6-4. Geometry and Timing for Various Intersection Types

Intersection Type	Radius RT (feet)	Distance XT (feet)	Turn Time TT (sec)
2 Lane, No Left	18.0	28.3	1.6
2 Lane, Left	24.0	37.7	2.1
4 Lane No Left	30.0	47.1	2.6
4 Lane, Left	36.0	56.5	3.1

Source: ARINC April 2012

There are two cases to consider for this application:

Case I: Vehicle A is stopped at the limit line and is waiting to execute the turn; In this case T_A is zero, and the system should warn the driver not to turn if the time to start and complete the turn (T_T) is less that the time for Vehicle B to reach the intersection (T_B). If this is not the case, then Vehicle A should simply wait.

Case II: Vehicle A is approaching the intersection. In this case the system should warn Vehicle A not to turn if the time (T_A) for Vehicle A to reach the intersection is either less than the time for Vehicle B to reach and cross the intersection (T_B+T_I), or the time for Vehicle A to reach the intersection and complete the turn (T_A+T_T) is greater than the time for Vehicle B to reach the intersection (T_B).

In both cases both the positions of both vehicle's may be in error, so the position accuracy requirement associated with either of the vehicles must be the application position error divided by the square root of two. This means that the errors of bother vehicles are combined using the root sum square method (the errors are assumed to be the same for both vehicles).

For either case, the false positive situation is that the reported position of Vehicle A or Vehicle B is closer to the intersection than it actually is. The false negative situation is that the reported position of Vehicle A or Vehicle B is farther from the intersection that it actually is. These situations are illustrated in Figures 3.4-2 through 3.4-5 below.

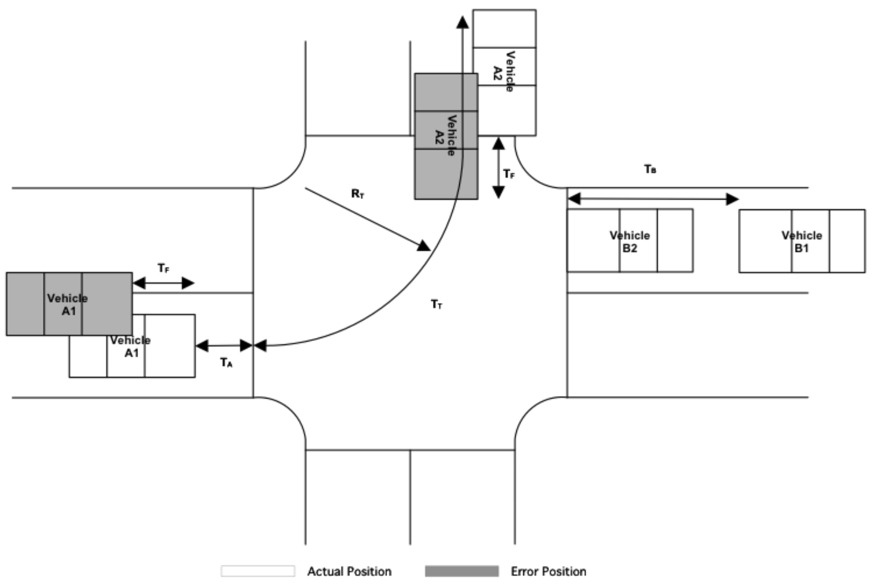


Figure 1.6-2. Left Turn False Positive Vehicle a Position
Source: ARINC April 2012

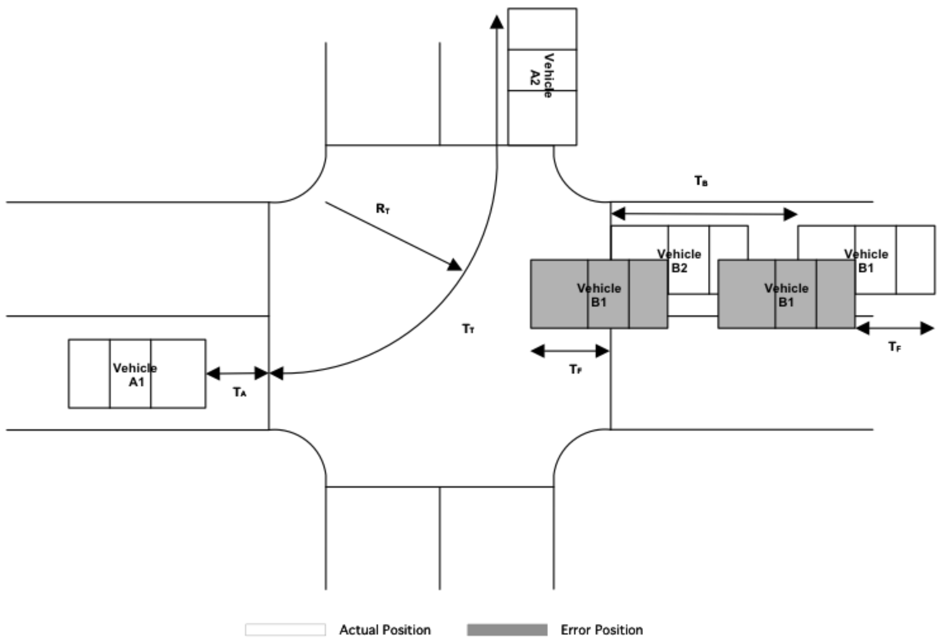


Figure 1.6-3. Left Turn False Negative Vehicle B Position
Source: ARINC April 2012

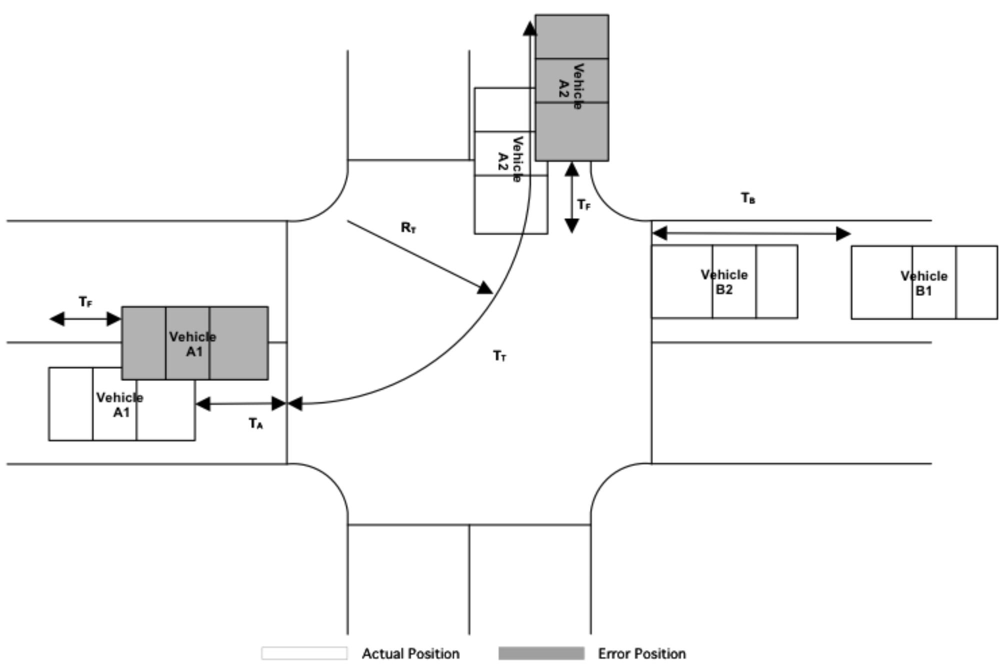


Figure 1.6-4. Left Turn False Negative Vehicle a Position
Source: ARINC April 2012

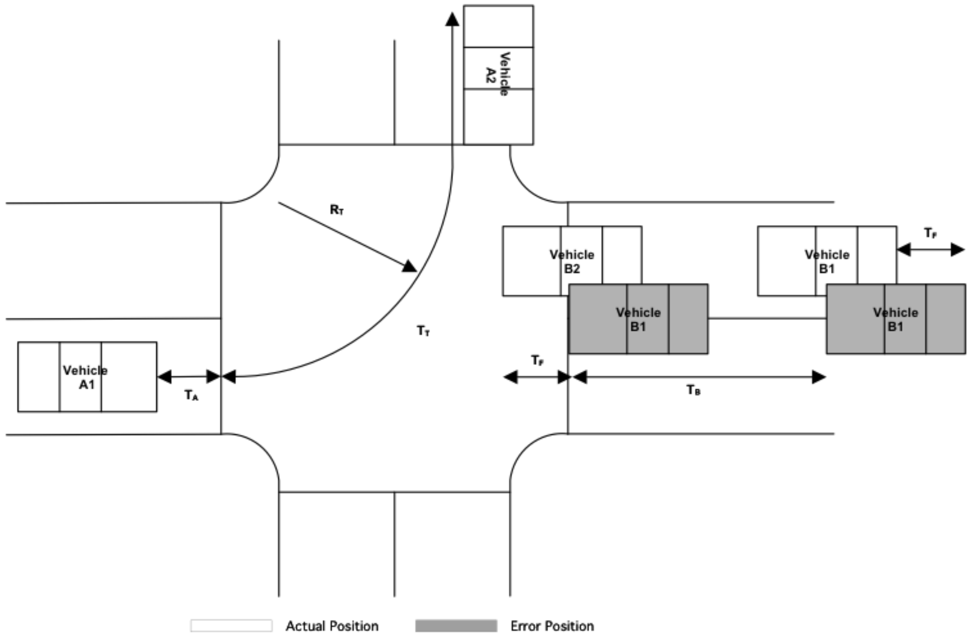


Figure 1.6-5. Left Turn False Negative Vehicle B Position
Source: ARINC April 2012

To determine the requirements for this application, it is necessary to decide how much margin to allow between the false positive and false negative situations. In general, false negatives are to be avoided, so it is appropriate here to bias the decision in favor of false positives. It seems reasonable to assume that warning against a left turn when the actual situation allows for one full vehicle length of margin would be acceptable, so, under this assumption, the distance associated with T_F would be one car length. Under this assumption a false positive error would occur if the positioning system placed the opposing vehicle at the limit line when it was actually one car length away from the intersection entry point, and a false negative error would occur when the system placed the vehicle one car length away from the intersection when it was actually at the intersection entry point. These assumptions maybe too conservative, but they would assure that only one of the vehicles was in the intersection at any given moment.

Because there are two vehicles, it is possible to have position errors reported for both Vehicle A and Vehicle B. Since it is reasonable to assume that these errors are random and have equivalent sources (i.e. they arise from the same types of error mechanisms), the root sum square value of the errors for both vehicles must be less than the application requirement of one vehicle length. This means that, if the errors are evenly applied to both Vehicle A and Vehicle B, the resulting error requirement for each vehicle is $0.7071(L_V)$, where L_V is the length of the vehicle. For passenger vehicles, this is typically about 18 feet (5.5 meters), so the longitudinal positioning requirement is 12.7 feet (3.9 meters), and the error radius is 6.35 feet (1.8 meters).

Unlike through signal warning applications, the left turn assist does not appear to require any significant lateral positioning accuracy unless the system is expected to be automatically activated based on the vehicle being in a turning lane.

As with other intersection related warnings, the ASIL level is assumed to be level B, with a corresponding position confidence requirement of 99.7%.

1.6.5 Route Guidance

The route guidance application is very simple. The system must provide turn maneuver indications to inform the driver of the next turn to take in order to follow the route. In general, the turn indication must be made late enough to avoid confusion about turning too early, and must be made early enough to prevent telling the driver to turn when he is already at or past the point where the turn should have been initiated. Generally this last point is the location at which the driver must brake to slow to a speed at which the turn can be safely made.

Assuming the worst case situation where the through light is green, the vehicle will be traveling at the posted speed limit. The worst case is a right turn, which in a residential area has a nominal inside radius of 7.6 meters (25 feet). Thus turn must be negotiated at about 5 mph to avoid excessive lateral acceleration (e.g., less than 0.5 g or so). Table 1.6-5 provides the deceleration distance, the response, and brake activation distances for various speeds.

Table 1.6-5. Perception, Brake Engagement and Stopping Distance versus Speed

	Speed (mph)			
Perception Time (Sec)	30	45	60	75
1.00	44	66	88	110
1.25	55	83	110	138
1.50	66	99	132	165
1.75	77	116	154	193
2.00	88	132	176	220
Reaction Time (Sec)	**Brake Engagement Distance (ft)**			
0.30	13	20	26	33
Deceleration Level (g)	**Slowing Distance (ft)**			

0.30	32	83	157	254
0.50	19	50	94	152
	Total Distances (ft)			
False Positive	101	235	359	507
Nominal	112	202	315	452
False Negative	77	136	209	295
	Distance Between False Positive and False Negative Points			
Feet	24	99	151	212
Meter	7.3	30.2	46.0	64.5

Source: ARINC April 2012

Here we have assumed a nominal deceleration of 0.3 g, and a worst case deceleration (in the false negative situation) of 0.5 g. The slowing distances are the distance required to slow from the current speed to the 5 mph turning speed. As can be seen in the table, the difference between the false positive and false negative points is 24 feet, or 7.3 meters. This implies an error radius of about 12 feet, or 3.7 meters. This value is somewhat smaller than expected, since conventional wisdom has held that a navigation system can operate effectively with about 10 meter accuracy. However, systems operating with this level of accuracy do not typically perform well in terms of alerting the driver on time, and false positives and negatives are common with these systems. The fact that the result of an error is not dangerous, however, means that the ASIL is level QM. The apparent confidence level at this accuracy is 60%.

1.6.6 Lane Departure Warning

The lane departure warning application determines if the vehicle is drifting out of the lane of travel, and generates a warning to the driver about this situation. The physical setup for this application is shown in Figure 1.6-6 below.

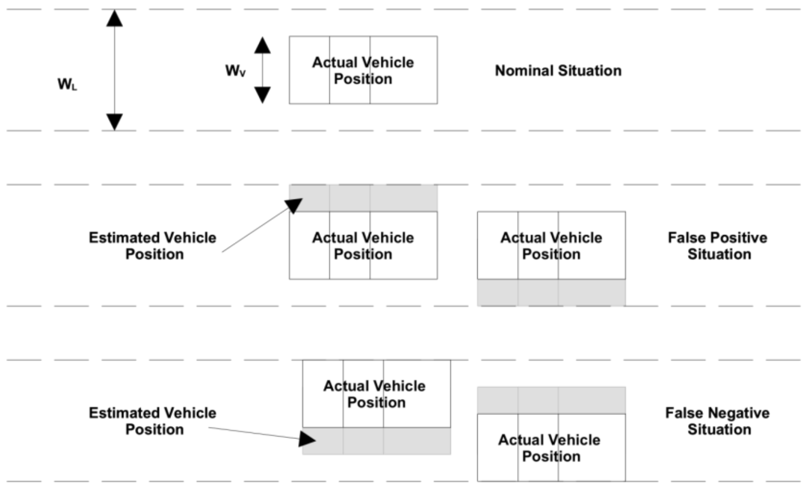


Figure 1.6-6. Lane Departure Warning Application Physical Setup
Source: ARINC April 2012

As can be seen from the Figure 1.6-6, the nominal situation occurs when the vehicle is in the center of the lane, and the position estimation places the vehicle in the center of the lane. The false positive situation occurs when the vehicle position is estimated to be at the edge of the lane (where the body of the vehicle is right at the edge of the lane line), when, in fact the vehicle is in the center of the lane. The false negative situation occurs when the vehicle is actually at the edge of the lane, but the position estimate places it at the center of the lane. The difference between nominal and false positive situation is the distance between the vehicle edge and the lane edge in the nominal situation. This is given by $(W_L-W_N)/2$, where W_L is the width of the lane, and W_V is the width of the vehicle. Similarly, the difference between nominal and false negative situation is also $(W_L-W_N)/2$. So, the total difference between false positive and false negative, that is, the required positioning accuracy, is W_L-W_N.

For nominal lanes of 12 feet width, and nominal vehicles of 8 foot width (the maximum legal width), the required position accuracy is thus 4 feet (1.2 meters). It is assumed that a collision might occur at twice this distance (assuming the other vehicle is in a nominal lane position). Lane change collisions are generally very low speed, and the risk of fatality is low, so this implies a SIL at level QM with a corresponding confidence level of 60%

The lateral motion of the vehicle during a lane drift is relatively slow. A typical intentional lane change takes about 3 to 5 seconds, depending on speed, so latency is not particularly critical in this application.

1.6.7 Lane Change Warning (e.g. Blind Spot)

The lane change warning application warns the driver if there is another vehicle in the adjacent lane when a lane change is initiated. In this case, the false positive situation occurs when an adjacent vehicle is either one full lane away, or is behind the host vehicle in the adjacent lane at a distance that would be acceptable to change lanes, yet the system estimates that the vehicle position is in the adjacent lane. The false negative point occurs when the actual position of the vehicle is in the adjacent lane, but the system estimate the position as being in the next lane over. In general, the situation where the vehicle in the adjacent lane, but is far enough behind to allow a safe lane change are not as limiting, so they will not be considered. These situations for this application are shown in Figure 1.6-7 and Figure 1.6-8 below.

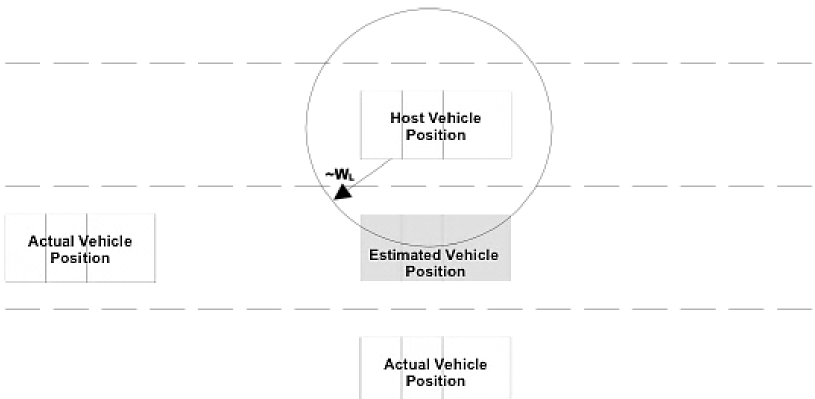


Figure 1.6-7. False Positive Lane Change Situation
Source: ARINC April 2012

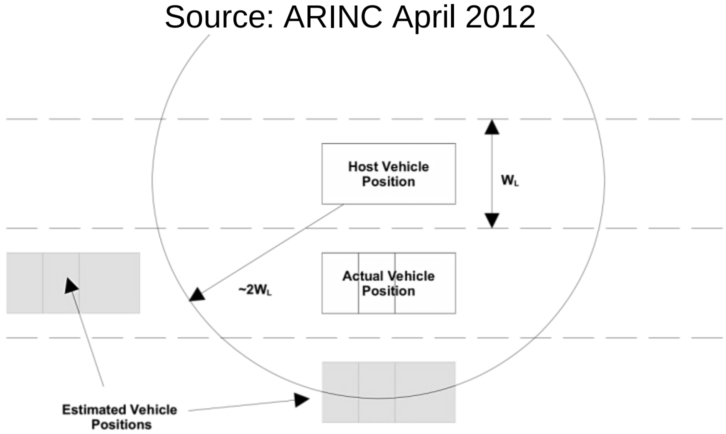


Figure 1.6-8. False Negative Lane Change Situation
Source: ARINC April 2012

As can be easily appreciated from the figures associated with this application, the difference in position between the false positive and false negative situations is approximately one lane width, or about 12 feet, so the allowable positioning error radius is about 6 feet. However, if the position of the other vehicle is also measured using the same system (for example, both vehicles using GPS and one communicating its position to the other) then the allowable relative position error is 12 feet, and the position error allocated to each vehicle is 8.5 feet, or an error radius if 4.25 feet (1.2 meter). As with lane departure, the consequences of a lane change accident are typically minor, so the ASIL is QM+ with a corresponding confidence of 76.9%.

The lateral motion of the vehicle during a lane change is relatively slow. A typical lane change takes about 3 to 5 seconds, depending on speed, so latency is not particularly critical in this application.

1.6.8 Lane Guidance

The lane guidance application is not substantially different from a positioning perspective as the lane departure warning application. The primary difference is that for guidance, there is a substantially higher need for low noise, or for noise resistance in the control algorithm. However, from a simple positioning accuracy perspective, the requirements for Lane Departure apply here as well.

1.6.9 Lane Gate Detection

A lane gate application is any application that takes action when the vehicle is within a defined section of the road. A typical type of gate is one lane wide and only long enough to detect a single vehicle; essentially a ½ vehicle long one lane wide spot on the road. This type of gate might be used, for example, to detect entry into a high occupancy toll (HOT) lane, a toll plaza, or a weigh-in-motion facility.   As shown in Figure 1.6-9 below, the lane gate application is sensitive to two types of positioning error. Longitudinal (along the axis of motion) position errors will produce a false positive error when the vehicle is not actually more that 50% inside the lane gate region but the estimated position indicates that more than 50 of the vehicle is inside the region. The false negative decision occurs when more than 50% of the vehicle is inside the region, but the system estimates it as being outside the region. In these situations, it is clear that the position difference between these two error situations is ½ a car length, so the longitudinal error radius is about ¼ car length, or about 4 to 4.5 feet (1.2 to 1.5 m).

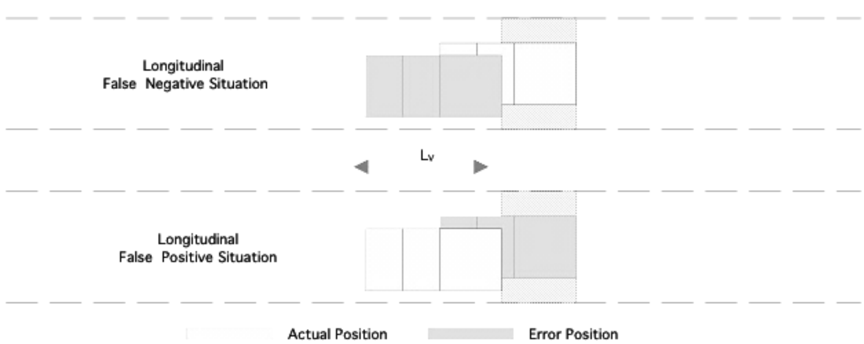


Figure 1.6-9. Longitudinal Lane Gate Position Errors
Source: ARINC April 2012

This requirement does not have particularly stringent confidence limits; however, since the vehicle is moving, it is highly likely to be estimated as passing through the lane gate, and an early or late detection is only important relative to various transaction and/or enforcement equipment. For example, if a camera is used to verify the presence of the vehicle, then the vehicle needs to be actually present when the camera is triggered. This means that the latency of the position estimate must be the time the vehicle takes to travel 1/4th of the length of the lane gate at its current speed.

Table 1.6-6 below summarizes the latency as a function of vehicle speed for various length lane gates. It is important to note that the length of the lane gate must be small enough to assure that the system can differentiate two vehicles driving at close separations, and this will tend to drive the latency requirement.

Table 1.6-6. Lane Gate Positioning Estimate Latency (Sec)

	Vehicle Speed (mph)				
Lane Gate Length (feet)	**30**	**40**	**50**	**60**	**70**
4	0.09	0.07	0.05	0.05	0.04
8	0.18	0.14	0.11	0.09	0.08
16	0.36	0.27	0.22	0.18	0.16
32	0.73	0.55	0.44	0.36	0.31

Source: ARINC April 2012

The more problematic case involves lateral position errors. Here it is possible to miss the vehicle entirely, or to accidentally estimate a vehicle in an adjacent lane as passing through the lane gate. A missed detection might result in a missed fee charge, and an accidental detection would result in a vehicle being inappropriately charged. This situation is illustrated in Figure 1.6-10 below.

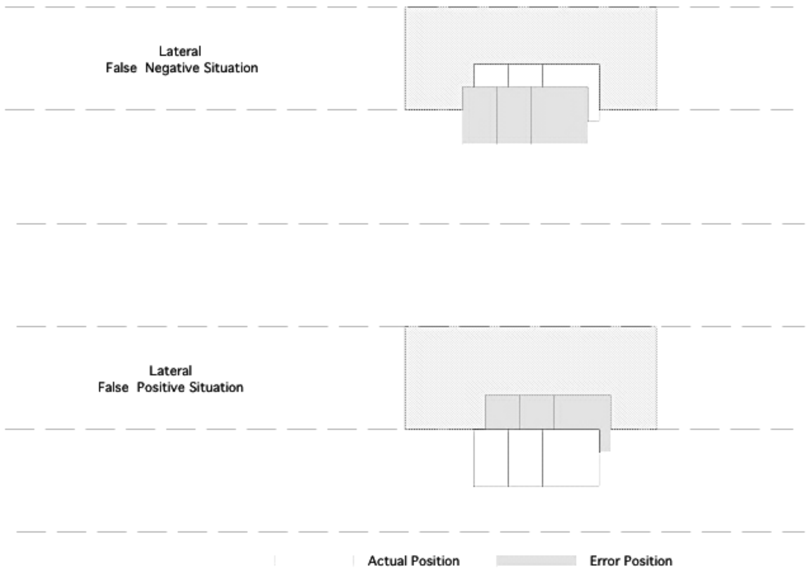


Figure 1.6-10. Lateral Lane Gate Position Errors
Source: ARINC April 2012

As can be appreciated from Figure 3.4-10, the difference in position between the false positive and false negative situations is the width of the vehicle. So, the overall tolerable error radius is about 2 feet (0.6 meter).

The confidence requirement depends on the willingness to risk missing detection or accidentally charging the wrong vehicle. Generally, since this is not a safety of life application, the confidence can be estimated at about 60%.

1.6.10 Probe Data Collection

The probe data collection application is relatively simple. Vehicle data such as travel speed is collected and correlated with the time and position that it was collected. In general, the positioning requirements depend heavily on the intended use of the data. For example, if the objective is to identify specific road condition information, then the requirement may be a radius of about 1/2 lane width (6 feet), so that the specific lane for the incident may be determined. The latency for the position is typically not critical, although the position error radius must include any offset for positioning reporting latency.

This application does not involve any substantive or direct safety concerns, so the ASIL is level QM with a corresponding position confidence level of 60% (or less).

1.6.11 Automated Braking

The automated braking application is similar in nature to the MUTCD warning and the intersection violation warning applications, in terms of positioning requirements.

A typical automated braking scenario includes the vehicle approaching an obstacle that it must stop for. The obstacle may be a real object in the roadway such as a stopped vehicle, or it may be a virtual barrier, such as the intersection limit line for a controlled intersection (e.g., a stop sign controlled intersection or a signalized intersection in the red phase).

The physical setup for the automated braking scenario is shown in Figure 1.6-11.

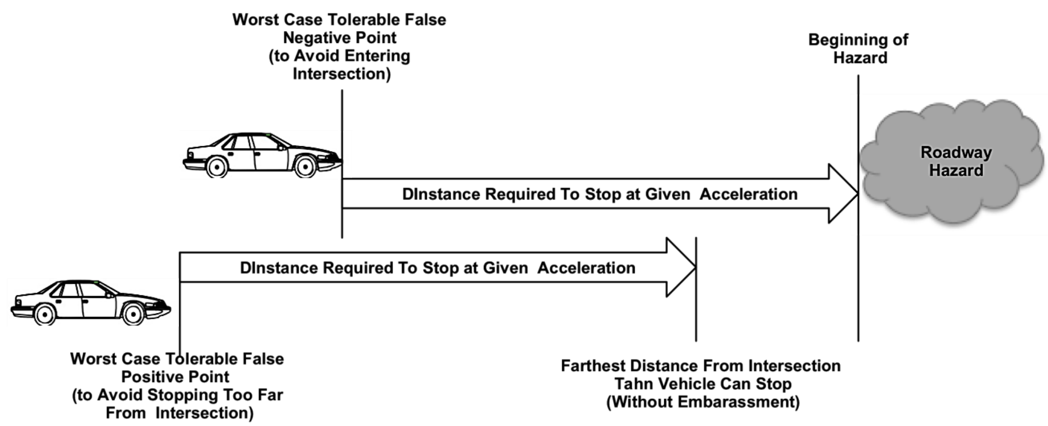


Figure 1.6-11. Automated Braking Physical Setup
Source: ARINC April 2012

As can be seen in Figure 3.4-11, the false positive point for this application occurs when the application decides to begin braking (based on vehicle position and speed) at a point where it will come to a stop at a distance from the hazard that is just acceptable (but no farther). The false negative point occurs when the vehicle stops just at the hazard. While the distance from the hazard that is "acceptable" to stop is highly subjective, generally drivers seem to measure these distances in terms of vehicle lengths (it is unclear if this applies equally to large vehicles like trucks). For a passenger vehicle, stopping more than one vehicle length from an obstacle would seem odd. This is especially obvious if the obstacle is, for example, an intersection limit line. The false negative threshold is obviously at the obstacle itself. So the overall difference between the false positive and false negative points is one vehicle length (about 18 feet (5.5 meters)). The resulting position error radius is half this distance, or 9 feet (2.75 meters).

The lateral position accuracy requirement depends on the type of obstacle. Assuming the obstacle is one lane wide the lateral requirement is the same as for lane gate applications. However, since this is a discontinuous automated application, the SIL is slightly higher (see Table 3.3-4). For this application the ASIL is level B or possibly level C with a corresponding position confidence between 99.7% and 99.97%.

Latency is also critical in this application. Systematic latency can be compensated for by projecting the reported position forward based on the vehicle trajectory. However, any uncertainty in the latency will be realized as position error, and this must be accommodated in the overall error budget. For example, typical GPS latency is about 80 msec to 100 msec. The exact value depends on the specific satellite constellation, noise, etc. A variation of ±10 msec at 60 mph (about 100 kph) is 0.88 feet (0.26 meters). Since this error is independent from the other position errors, we can use the Root Sum Square (RSS) approach to determine the allowable position error that remains after removing the allocation for latency; however; this added error does not make any significant difference in the requirement.

1.6.12 Crossing Path Collision Warning

The crossing path collision warning system is intended to warn the driver if there is a risk that a vehicle approaching the intersection from the right or left may reach the host vehicle's path before the host vehicle has exited the intersection. This is illustrated in Figure 1.6-12 below. In this figure, Vehicle A is traveling at some speed V_A, and Vehicle B is traveling at a speed V_B in a crossing path direction to Vehicle A. Vehicle A must warn the driver if it cannot cross through the intersection completely before Vehicle B enters the intersection. This application might be used as a backup to other intersection alert systems, or it might be used in situations where an intersection is uncontrolled. It is also useful in situations where one vehicle may be violating a traffic control; and putting the other vehicle at risk. For example, if one vehicle has the right of way (say a green light), and another vehicle is running the crossing (red) light, this application would warn the legally crossing vehicle of the impeding danger.

Obviously the system must thus be able to determine the lane of travel, which initially sets the lateral positioning requirements equivalent to the lane departure warning application. T_A is defined by $T_A=X_A/V_A$, where X_A is the distance from the front of Vehicle A to a point one vehicle length (about 18 feet for a passenger vehicle) past the intersection exit point (the far side limit line). T_B is defined by $T_B=X_B/V_B$, where X_B is the distance from the front of Vehicle B to the intersection limit line, and V_B is the speed of Vehicle B. It is important to note that the application is symmetrical, so Vehicle A and Vehicle B could be interchanged, and the requirements on each would also interchange. As a result it is not necessary to examine the various combinations of errors in the positions of vehicle A and B.

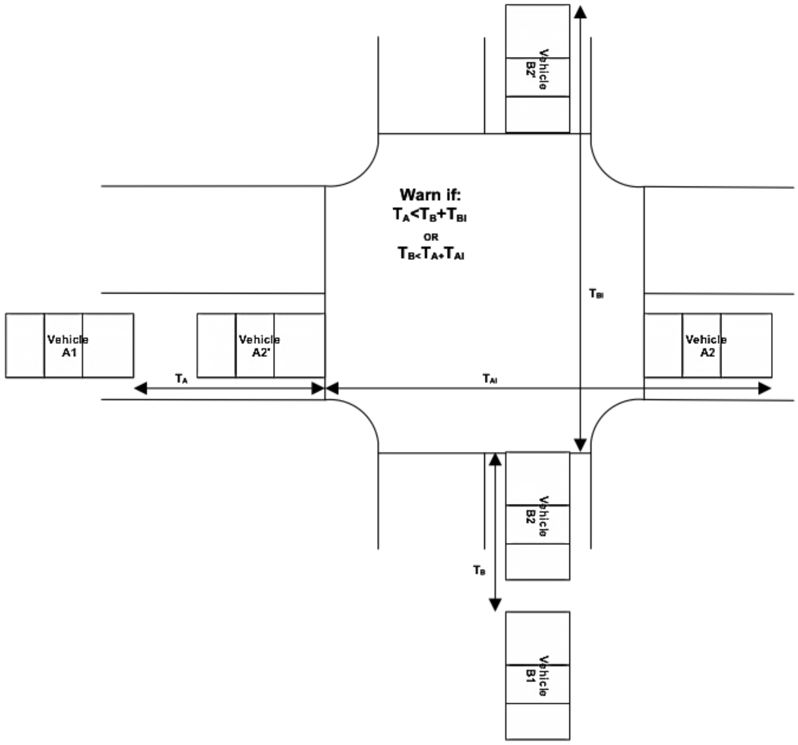


Figure 1.6-12. Crossing Path Physical Setup
Source: ARINC April 2012

In this application, the false positive situation occurs when either the reported position of vehicle A is farther from the intersection than the reported position, or the reported position of Vehicle B is closer than it actually is. In this situation, the system will decide that Vehicle B will enter the intersection before Vehicle A exits, and it will warn, even though Vehicle A will exit before vehicle B enters. These cases are illustrated in Figure 1.6-13 and Figure 1.6-14 below.

It is important to point out, that there are two other false positive situations. One situation is where vehicle A is reported at a critical point in relation to Vehicle B but in reality it is sufficiently far away from the intersection that Vehicle B can pass through before vehicle A arrives at the limit line. The other situation is where Vehicle B is reported at a critical position relative to Vehicle A, but in reality it is sufficiently far away that Vehicle A can pass through before Vehicle B actually arrives at the intersection. Either of these cases requires that the false positive error distance be at least the width of the lane being crossed (i.e. the time to cross the error radius is equal to the time for the other vehicle to cross the path of the other vehicle), so neither of these represents a limiting case from an accuracy requirements perspective.

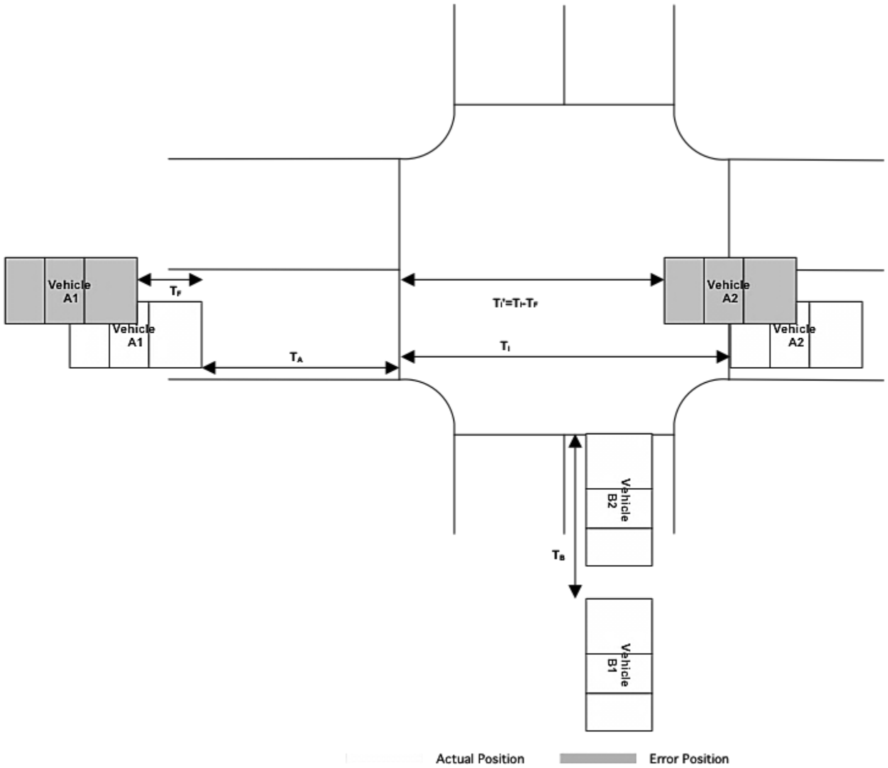


Figure 1.6-13. Crossing Path False Positive Situation Vehicle a Position
Source: ARINC April 2012

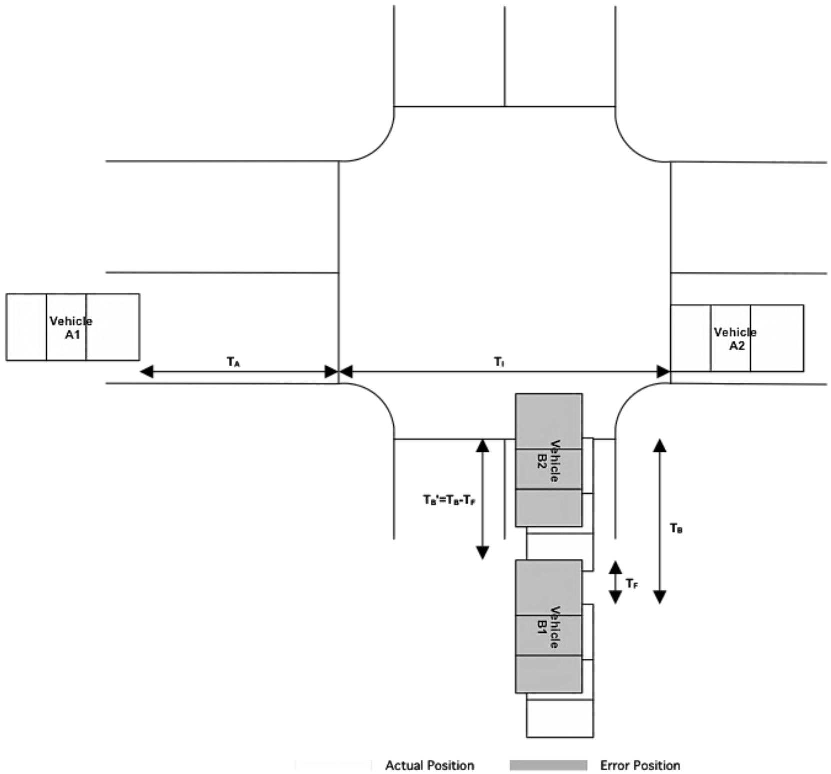


Figure 1.6-14. Crossing Path False Positive Situation Vehicle B Position
Source: ARINC April 2012

The false negative situations occur when the reported position of Vehicle A is closer to the intersection than it actually is, or when the reported position of Vehicle B is reported as farther from the intersection than it is. In either case, the system will decide that Vehicle A can cross the intersection before Vehicle B arrives, but vehicle B will enter before Vehicle A clears the intersection. This situation is illustrated in Figure 1.6-15 and Figure 1.6-16 below.

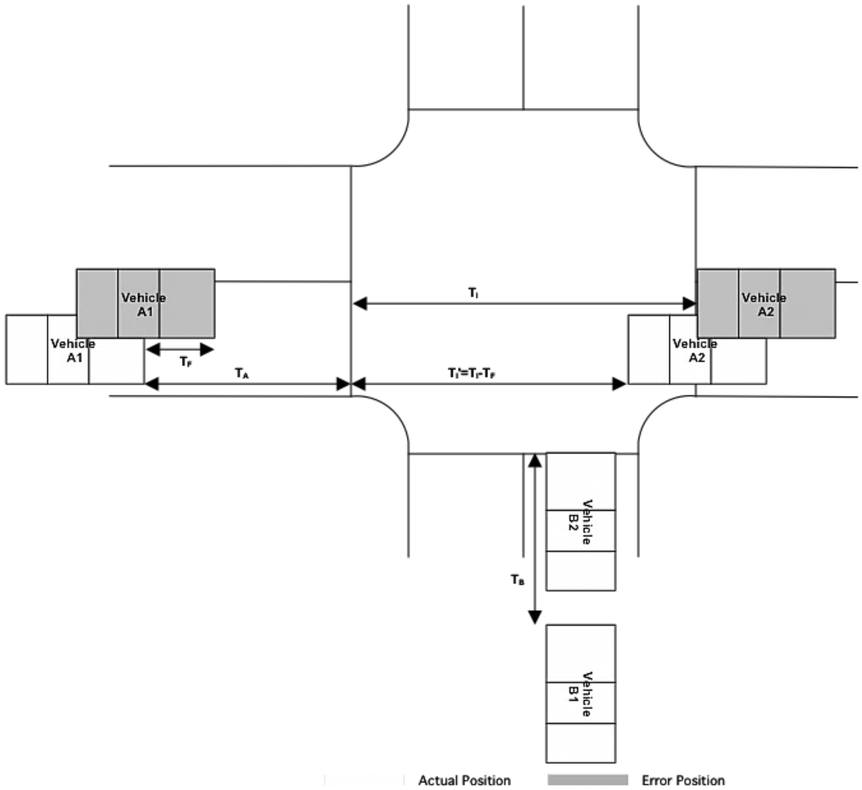


Figure 1.6-15. Crossing Path False Negative Situation Vehicle A Position
Source: ARINC April 2012

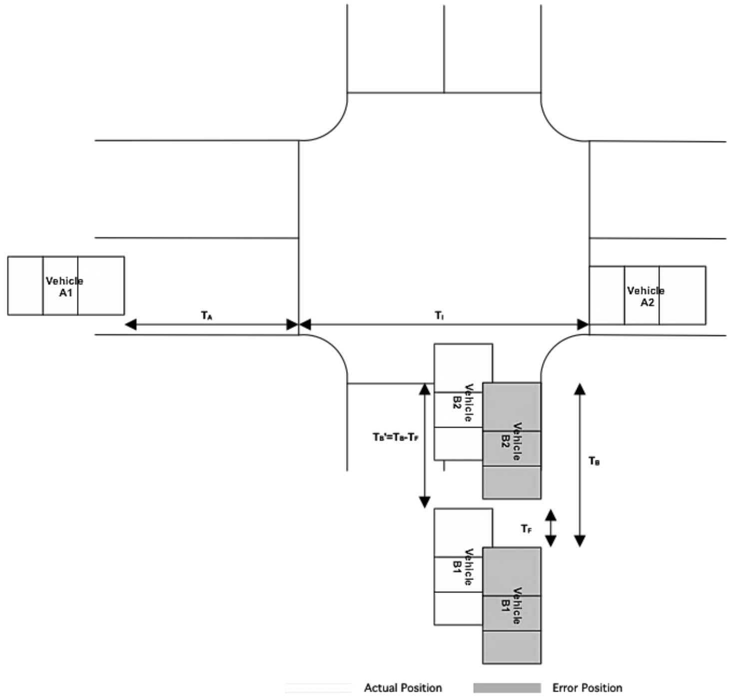


Figure 1.6-16. Crossing Path False Negative Situation Vehicle B Position
Source: ARINC April 2012

To determine the accuracy requirements for this application it is thus necessary to decide how far apart the two false decision points can be. In terms of safety, it is desirable to bias the system away from false negatives and toward false positives. An acceptable false positive case then appears to be warning when the opposing vehicle is expected to be within one car length of entering the intersection when the host vehicle is just exiting the intersection. This means that the overall error radius (the difference between the false positive and false negative points) is one half the length of the vehicle, or about 9 feet (2.8 meters). However, because both vehicles may be in error, this value must be allocated between both vehicles. Using the Root Sum Square (RSS) approach this equates to a position error for each vehicle of 12.8 ft (3.9 meters).

Because this application involves a potential for an intersection collisions, the potential for injury is present, although the potential for fatalities may not be particularly high, except for higher speed situations. Using an estimated ASIL level of B to C, the position confidence level requirement is 99.7% to 99.97%.

Lateral position errors in one vehicle are equivalent to longitudinal position errors in the other vehicle, so the same value applies to both lateral and longitudinal errors.

As with the lane gate situation, the latency in reporting the position has a substantial impact on the timing of the application, and since the vehicles are in motion, errors in timing are equivalent to errors in position. This means that the position accuracy budget must be allocated between the actual position error and the non-systematic component of the latency, which means that the actual positioning estimation accuracy requirement will be higher than stated above.

Chapter 4 Detailed Analysis of Candidate Positioning Technologies

This section of the report provides an expanded analysis of the positioning technologies reviewed in the Task 3 report of this project and identified in Task 3 as "worthy of additional analysis and consideration."

Each of the shortlisted technologies was examined to provide the following information:

- Overview of technology and basic operational principles and relevant subclasses of the technology;
- Assessment of performance relative to key performance parameters including:
    - Accuracy;
    - Confidence;
    - Latency;
    - Tracking Capability (as applicable);
    - Availability and Reliability;
- Analysis of current deployment compatibility from the standpoint of the vehicle environment and roadside environment including temperature/shock/vibration/weather-proof, size/weight, and power, and any other issues that may influence its deployment;
- Requirements for installation, test and calibration as well as frequency of servicing needs (such as re-calibration);
- Summary of applicable standards applicable to the sensor;
- Availability of interface standards compatible with vehicles;
- Cost and life cycle status;
- Potential improvements to the technology.

1.7 Global Positioning System

The Global Positioning System (GPS) is an obvious choice for vehicle based positioning. GPS offers reasonably good positioning accuracy and latency at low cost, and it is used widely in many current vehicle applications.

GPS devices are available in a wide variety of package types, configurations, electrical power options and environmental specification levels. These range from PC card implementations, module implementations, roof mount configurations and various types of handheld devices, as illustrated in Figure 1.7-1 below. Because GPS technology has become so pervasive, it has generally been reduced to a chip level function that can literally be integrated into almost any from factor

1.7.1 Overview of GPS Technology

The Global Positioning System (GPS) uses a constellation of orbiting satellites that transmit regular precisely timed signals. These signals are encoded in a way that allows a receiver on the ground to determine the time of arrival of each signal relative to the other received signals. Using this timing information, and the known positions of the satellites in their orbits, the receiver is able to determine what point in the geodetic coordinate system corresponds to that particular set of satellite positions and relative signal time offsets. The time offset for each signal corresponds to what is known as a pseudorange, because the time offset is mathematically related to the actual distance of the satellite from the receiver. Within the error limits, there is only one theoretical point that corresponds to the set of ranges from all of the observed satellites; this is the estimated receiver position.

Figure 1.7-1. Available GPS Receiver Types
(Source: Composite from Various GPS Receiver Manufacturers' Product Literature)

The review of available GPS receivers provided in the Task 3 report indicated that GPS devices were capable of providing four general levels of positioning capability:

- C/A code phase GPS receivers without differential corrections can provide a 50% CEP circle of about 10 meters radius;
- C/A code phase GPS receivers with differential corrections can typically provide a 50% CEP circle of about 2.5 meters radius;
- High performance C/A code phase GPS receivers with high accuracy low latency differential corrections can provide a 50% CEP circle of about 1 meter radius;

- Carrier Phase receivers with integer ambiguity information can provide a 50% CEP circle of 10 to 20 centimeters radius, although these typically require several seconds to resolve this level of accuracy.

Some applications also require altitude, and this would be represented by a spherical error radius. Because generally GPS altitude is less accurate, it is also realistic to represent these errors in terms of horizontal radii and vertical radii (e.g., an error ellipse). For the following discussion we have generally referenced horizontal errors, but the concepts apply to altitude errors as well. These different levels of capability derive primarily from physical limitations in the resolution of the information embedded in the GPS signals.

GPS is subject to a variety of other types of errors. These include:

- **Atmospheric Propagation Delays**: The largest error comes from propagation delays, especially through the ionosphere. This error is common to receivers in geographic vicinity, and it can be compensated through either externally provided differential corrections, or through the use of a multichannel receiver that uses the fact that different carrier frequencies are affected differently by atmospheric effects. Generally, for externally provided corrections, the closer to the correction station the receiver lies, and the shorter the time span between the current measurement and the generation of the correction, the more accurate the correction will be, although it is also possible to interpolate between stations if data from two or more stations can be received;
- **Multipath**: Close to the ground, the receiver may not have a line-of-sight signal from a satellite, and instead may receive signals reflected from buildings and terrain. It may also receive both line of sight and reflected signals. This is independent for all receivers, and may vary substantially as the receiver moves. In its simplest manifestation, multipath will cause substantial phase differences between the direct and reflected signals, and this may make it difficult to accurately discriminate the signal at all, or it may spread the PN code timing over time, making it difficult to resolve the code to determine the pseudorange of that satellite. In its more problematic form, multipath can create ghost pseudoranges that, if used with other pseudoranges, may cause the position estimate to be significantly off. After code resolution errors and atmospheric delay contributions, multipath is the largest random error component in GPS position. It is especially problematic in the mobile environment because the receiver is expected to be moving through a complex multipath environment, and the multipath effects are thus always changing;
- **Signal Dropouts:** GPS is a line of sight system, so if the host vehicle drives under a bridge or into a tunnel, the receiver will be unable to determine a position fix;
- **Ephemeris errors and satellite clock drift:** The satellite's orbit may be slightly different from that broadcast. Satellite clocks may drift as much as 7 nanoseconds which means the position of the satellite may be measured as off

by 210cm. This error is consistent for all receivers using information from that satellite, but may result in different error for different receivers depending on where they are and how they use which satellites.

After differential corrections have been applied, code phase receivers are inherently limited by how accurately the C/A code offset can be measured. Each code “chip” represents a time interval of one microsecond, and each microsecond thus represents a pseudorange increment of 300 meters. Obviously most C/A code based receivers are able to resolve the pseudorange offset to much better than one chip. In fact typical resolution is about 1% of the chip duration, or 3 meters. Resolution beyond this level becomes increasingly problematic due to phase noise in the receiver oscillators and amplitude noise on the discriminated code signal that masks the effect of small changes in the matched filter output that might otherwise result from small shifts in the code time offset.

Generally the next step in receiver accuracy is to use carrier phase positioning. This approach reduces the error to a few centimeters, but it typically either requires externally provided ambiguity resolution information (to determine which cycle of the carrier represents the start of the code sequence), or it requires multiple frequencies and substantial dwell time at a single position. In mobile applications some high performance systems use a stationary “survey grade” multichannel receiver and a roving carrier phase unit. The stationary unit determines the carrier ambiguity and provides this to the roving unit by way of a short range wireless communications system.

Task 3 report identified carrier phase based GPS as a potentially useful positioning technology. Analysis carried out in Task 4 identified two different approaches to using carrier phase. These are discussed in the sections below.

1.7.1.1 Carrier Phase Receivers

The use of carrier phase measurements from a GPS receiver provides the most accurate position determination among other possible positioning algorithms with GPS measurements.

The typical approach is to use double differences on the phase measurements. One satellite tracked by both receivers is selected as the reference satellite. The phase measurements of all other satellites tracked in common by the two receivers are differenced with each other, and also with the difference in the phase measurements of the reference satellite. To make this clear, let ϕ_A^i be the phase measurement of satellite *i* for receiver *A*, the reference receiver, and ϕ_B^i be the phase measurement of satellite *i* for receiver *B*, the remote receiver, for $i = 1, 2, \ldots, n$ where *n* is the number of satellites tracked in common by the two receivers. Selecting satellite *1* as the reference satellite, $n - 1$ double differences are computed as:

$$\nabla\Delta_{AB}^{i} = \phi_B^i - \phi_A^i - \left(\phi_B^1 - \phi_A^1\right)$$

for $i = 2 \ldots n$. Double differencing is used since differencing the phase measurements with a reference satellite removes the clock bias errors from both receivers. Differencing the phase measurements between receivers will remove common mode errors, which will include atmospheric errors when the receivers are relatively close.

The phase measurements can be made to fractions of a wavelength. For the L1 carrier at 1575.42 MHz, the wavelength is approximately 19 cm, and the L2 carrier at 1227.6 MHz has a wavelength of about 24.4 cm. Therefore the phase measurement noise is usually on the order of a millimeter or so, and the double differenced measurement still has very small noise, on the order of a couple of millimeters.

Although the phase can be measured very accurately, the whole number of wavelengths is unknown. This unknown is referred to as the integer ambiguity. To make use of the phase measurements for positioning, the integer ambiguity has to be determined first. There have been many algorithms used to solve for the ambiguities. The most widely used is probably the LAMBDA method, developed by P. J. G. Teunissen at the Delft Geodetic Computing Center at Delft University of Technology in the Netherlands in 1993.

The determination of the integer ambiguities can be simplified by using dual frequency receivers. The phase measurements are combined to obtain the beat frequency of (575.42-1227.6=) 347.82 MHz, which has a wavelength of 86 cm, the “wide lane” wavelength. Using the wide lane measurements reduces the time to resolve the ambiguities by reducing the number of potential ambiguities, and also increases the probability of a correct resolution.

Accurate position can be maintained as long as enough signals are tracked without error. One such error is a cycle slip, which is a jump in the integer number of cycles. Cycle slips may be caused by signal attenuation due to temporary obscurations, loss of the signal, or multipath. Often times a receiver will detect the cycle slip and may even repair it. Generally the magnitude of the error is proportional to the number of slipped cycles.

When used in real-time, this positioning approach, known as real-time kinematic (RTK), supports the most demanding positioning application requirements.

Kinematic positioning is a relative system. The position of one GPS receiver (antenna) is found very accurately with respect to a second GPS receiver (antenna). The second receiver’s antenna may be fixed at a surveyed location, or it may simply be allowed to resolve a high accuracy position by being fixed at that position over some time period. By comparing pseudoranges for the two receivers, the absolute position of the first receiver can be determined precisely. The first receiver whose position is being computed is known as the remote or roving receiver. The second receiver, whose position is usually stationary, is the reference receiver.

This arrangement is illustrated in Figure 1.7-2 below.

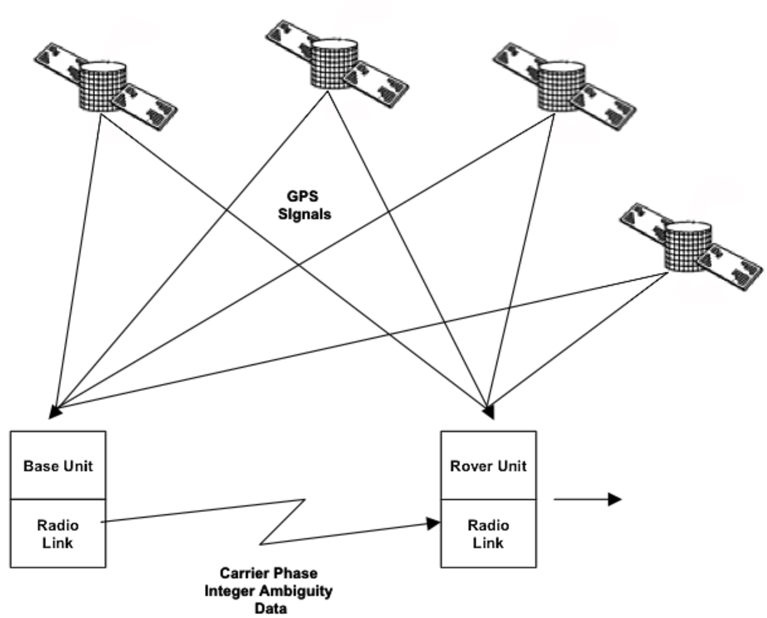


Figure 1.7-2. Typical RTK GPS System
Source: ARINC April 2012

The position accuracy degrades as the separation between the reference and remote receivers increases, primarily due to the differences in ionospheric effects. The errors due to the ionosphere can be mitigated by using dual frequency receivers and measuring the ionosphere or by using a network of reference stations and obtaining estimates of the atmospheric errors [1]. With very long baselines, the effects of ephemeris errors contribute to the RTK position error [2].

The reference receiver data must be transmitted to the remote receiver. Consequently a data link is required that may be filled by the DSRC. The roadside equipment must then have a data link to the facility that contains the reference receiver for disseminating the data to the users.

The time-to-first-fix (TTFF) for the RTK position is dependent on several factors, including whether single or dual frequencies are used, length of the baseline (distance between reference and remote receivers), the multipath environment, and obscurations, such as trees overhead. These factors also affect the probability of correctly fixing the ambiguities. The TTFF includes not only the normal time a GPS receiver needs to acquire and track the signal-in-space, but also the time required to fix the ambiguities. The time to find the ambiguities can range from several seconds to several minutes [4, 5].

1.7.1.2 Carrier Smoothed Code Phase Receivers

Several approaches have been developed to make use of carrier phase information without the provision of externally generated integer ambiguity information. As described above, the limitation of using the carrier phase to accurately determine the pseudoranges is that the carrier signal is so uniform that it is possible to be off by an integer multiple of full cycles; a problem known as “integer ambiguity”. It is possible, however, to use changes in the *relative* phase of the signals to measure small changes in the pseudoranges. These methods use a specialized Kalman filter (known as a Hatch filter) to track the changes in carrier phase between GPS epochs.

A Kalman filter combines measured results and modeled results in a way that minimizes the overall uncertainty of the solution. The modeled result is important since one generally knows from physics how the measured quantity is supposed to change. The Kalman filter essentially compares the measured value from the predicted (modeled) value and produces an improved estimate of the value. In GPS this can be used in a variety of ways. For example, one knows that motor vehicles move in particular ways. They do not, for example, move sideways in the same way as they move forward, and they have finite limits to lateral and longitudinal acceleration. Using these characteristics it is possible to create a predictive model that can infer a future position from an estimated position based on the measured state of the vehicle. This estimate is then compared to the measured position and a new, lower uncertainty estimate is generated.

Carrier Smoothing uses a special type of Kalman filter to predict the position or the pseudoranges as the vehicle moves. This is known as a Hatch filter. Reference [8] provides a useful description of the approach. As the position changes the carrier phase will also change in a predictable way. These changes in carrier phase are then related to either changes in pseudorange (what is known as Range Domain Filtering-- RDF), or to changes in overall position (known as Position Domain Filtering -- PDF).

In RDF, each pseudorange is determined using code offsets, and these offsets are then used together with the change in carrier phase between consecutive GPS epochs to develop filtered values for the Pseudoranges. This approach is able to produce generally more accurate, and substantially more stable, position estimates, as shown in Figure 1.7-3 below, as compared to using only pseudoranges.

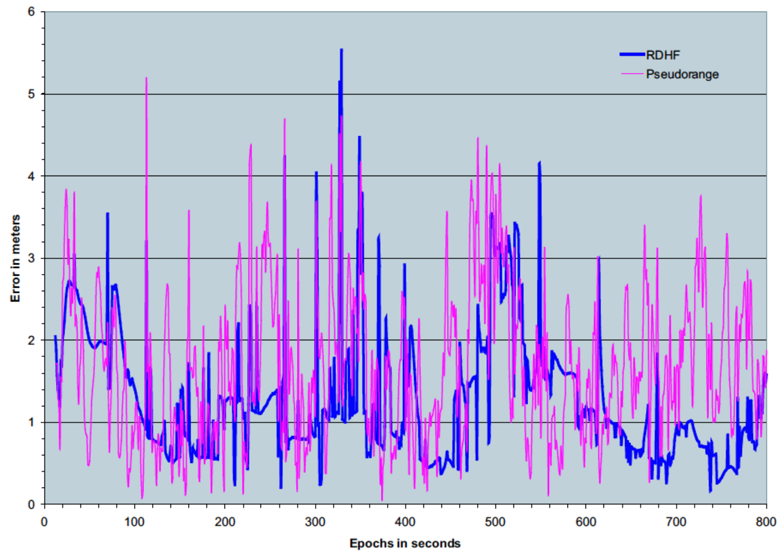


Figure 1.7-3. Position Error Results with RDF Process
(Ref: Thipparthi, S.N., "Improving Positional Accuracy Using Carrier Smoothing Techniques In Inexpensive GPS Receivers", A thesis submitted to the Graduate School in partial fulfillment of the requirements for the Degree Master of Science in Electrical Engineering, New Mexico State University, February 2004. [8])

The RDF process is outlined in Figure 1.7-4 below.

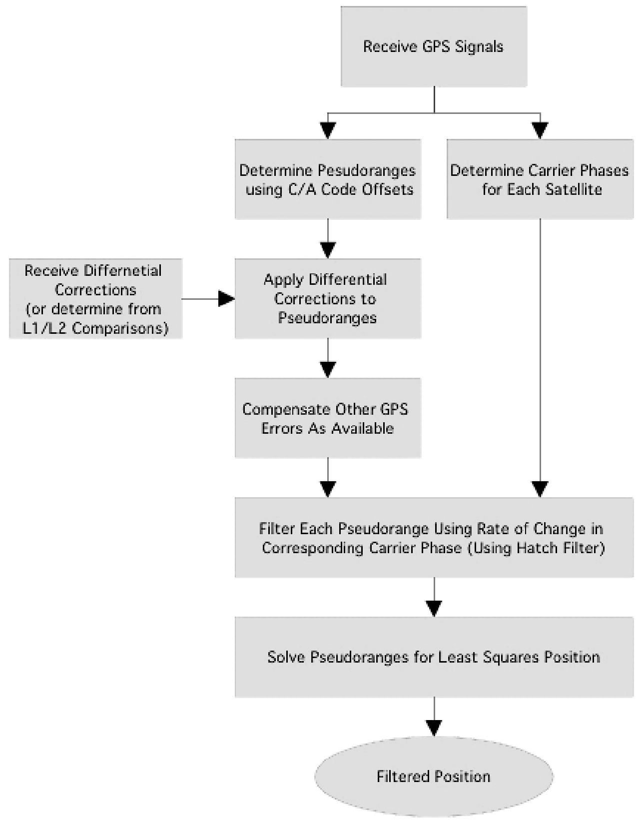


Figure 1.7-4. RDF Process

(Ref: Thipparthi, S.N., "Improving Positional Accuracy Using Carrier Smoothing Techniques In Inexpensive GPS Receivers", A thesis submitted to the Graduate School in partial fulfillment of the requirements for the Degree Master of Science in Electrical Engineering, New Mexico State University, February 2004 [8])

However, this approach assumes that the carrier phase for each pseudorange is tracked continuously. If a satellite signal fades or otherwise drops out, the effect is that that pseudorange is inaccurate and the overall position estimate suffers.

An alternative approach uses the same filtering process except it is applied in the position domain. In this process, known as Position Domain Filtering (PDF), a rough position estimate is derived from code phase determined pseudoranges. This position estimate is then filtered over time using a Kalman filter that includes the changes in carrier phase as an element of the position estimate model. In this way, small changes in position that would be unobservable using code phase offsets can be included in the estimated position. This is illustrated in Figure 1.7-5 below.

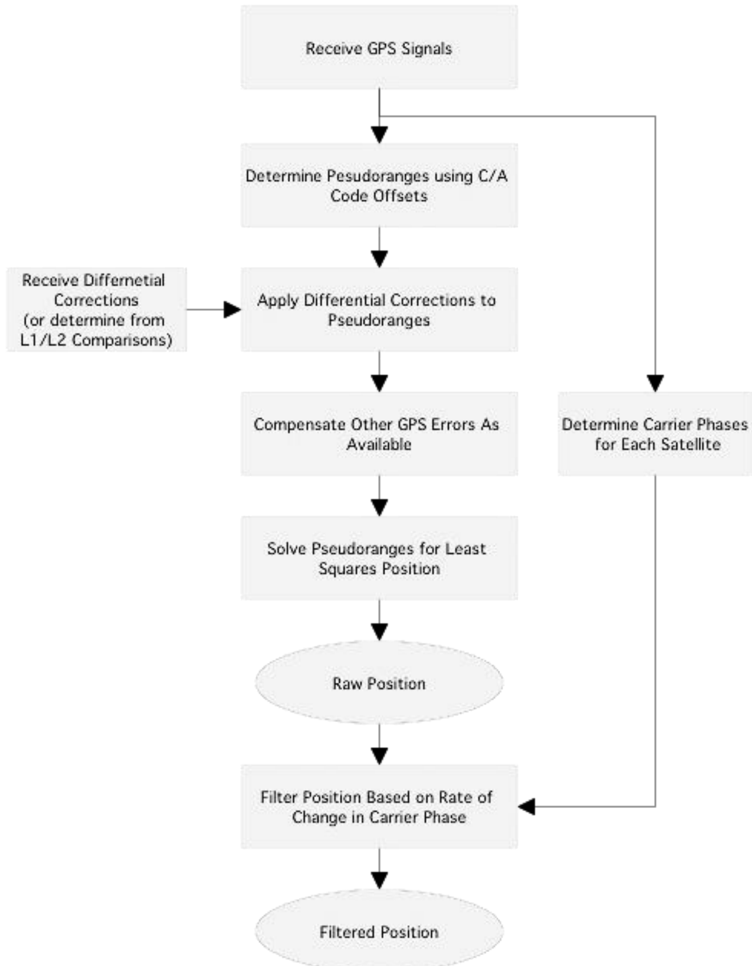


Figure 1.7-5. PDF Process
Source: ARINC April 2012

Example results using this approach are shown in Figure 1.7-6 below. As can be appreciated in the figure, the PDF position is much more stable and much more accurate than the position derived from pseudoranges alone. In addition, as illustrated in Figure 1.7-7, the position obtained using PDF is much less subject to errors caused by satellite dropouts than the position derived using RDF. In Figure 4.1-7 the green dots indicate points in time where the signal from one or more satellites is lost. Using RDF, the position experiences substantial brief error, while using PDF, this effect was not observed.

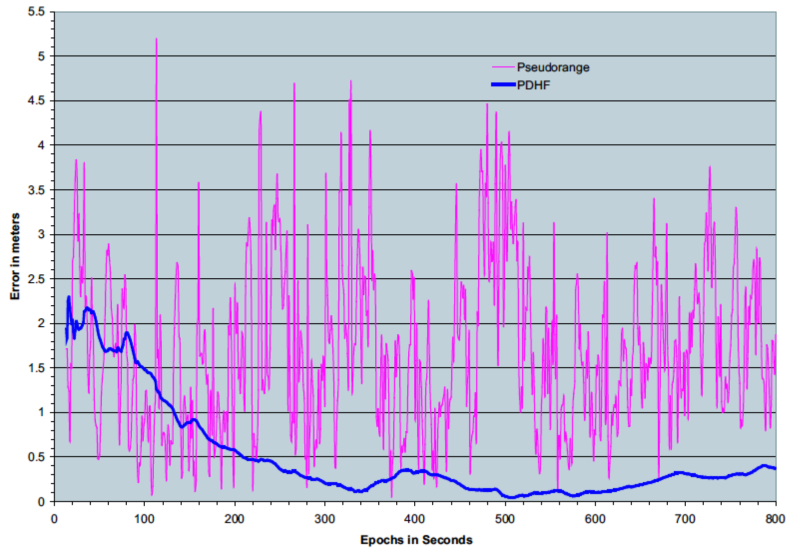


Figure 1.7-6. Position Error Using PDF
Source: ARINC April 2012

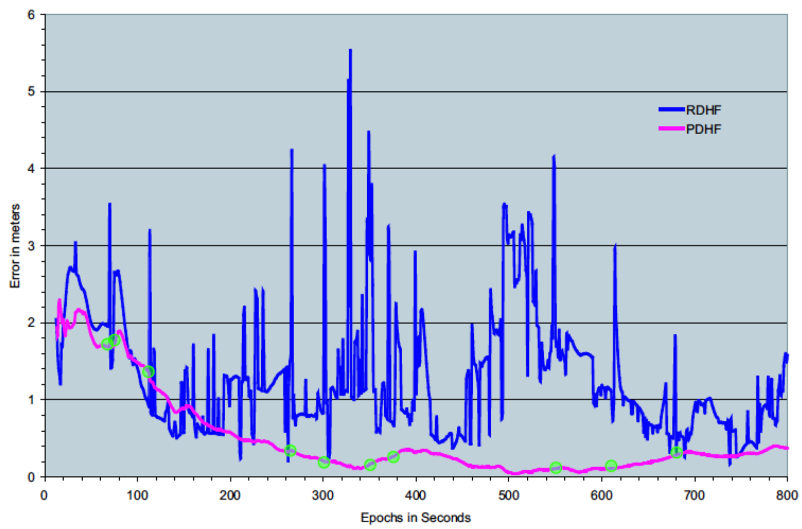


Figure 1.7-7. Comparative Position Errors Using PDF and RDF
Source: ARINC April 2012

It is important to note that the results shown in the figures above were obtained using a commercially available Garmin 17N (12 channel receiver) and a personal computer for software implementation. The Garmin 17N is a low cost WAAS compatible receiver typically used in recreational marine applications. It has a published uncorrected accuracy of about 15 meters at 95%, and a WAAS accuracy of about 3 meters at 95%.

Using PDF, this accuracy was improved to well below 0.5 meters. While promising, these results do not tell the entire story. Specifically, the measurements in the figures above were taken at a single fixed point. Under dynamic conditions, the filtering process is likely to add errors. It is also clear from the figures above that the system requires some settling time. It is unclear if the system will settle to the same level of accuracy if it is moving. A system that exhibits good performance only if it is stationary, or one that requires a long stationary startup cycle, is not realistic in the vehicle environment. However, the approach is promising, and it is possible that combining this method with inertial measurements (where the changes in carrier phase are predicted based on inertial measurements) would allow it to track properly under dynamic conditions. This same approach may also be able to improve the settling behavior. This approach bears further research.

1.7.2 GPS Performance Assessment

The critical limitations of GPS lie in the cost and ancillary infrastructure associated with reaching the higher accuracy levels, and a variety of limitations on availability, acquisition, and latency.

Differential correction data sources are well established, and generally available, but in many cases the correction source maybe relatively far from the receiver, and the timeliness of the correction data varies substantially.

Civilian GPS receiver accuracy falls into several general classes. Basic single frequency (L1) code phase GPS receivers appear to provide about 10-15 meters (32.8 -49.2 ft) accuracy. Adding differential corrections to these receivers improves accuracy to about 5 meters (16.4 ft).

A second class of single frequency receivers exhibits accuracy of around 2.5 meters (8.2 ft), which can be reduced to about 1 meter with suitable and timely differential corrections. Some receivers have been observed to provide sub meter accuracy under the right conditions. These receivers, often referred to as carrier smoothing code phase receivers, use a hybrid approach involving a combination of code phase detection and carrier phase tracking described above.

A third class of GPS receiver uses multiple frequencies (some combination of L1, L2 and L5) together with code phase and/or some version of carrier phase detection. The primary reason for using multiple frequencies is to provide point specific, near real time correction of atmospheric effects. So a multiple frequency receiver does not require external differential corrections. These receivers exhibit accuracies slightly better than their differentially corrected counterparts, depending on the detection method uses (e.g., code phase, carrier smoothed, etc.). They do, however, require substantial dwell time to resolve the various correction information.

A fourth class of receiver uses carrier phase detection with integer ambiguity information. These receivers typically use a fixed base receiver that supplies phase ambiguity and other correction data to a local “rover” receiver. The real time positioning accuracies for these systems are on the order of 10 centimeters (3.9 in). Post processing, and longer dwell times can reduce this to the millimeter level.

Table 1.7-1 provides examples of these receiver types together with general accuracy ranges.

Table 1.7-1. GPS Receiver Performance

Position Detection Approach	Signals Used	Accuracy (95% Error Radius)
C/A Code Phase Only	L1 Only	10.0 m to 15.0 m (49.2 to 32.8 ft)
C/A Code Phase Only with External Differential Corrections	L1 Only	3 m to 5 m (10.0 to 16.4 ft)
C/A Code Phase Only (internally developed atmospheric corrections)	L1/L2 (or L5)	2.0 m to 3.0 m (6.4 to 10.0 ft)
Carrier Smoothed C/A Code Phase with External Differential Corrections	L1 Only	1.5 m to 2.5 m (5.0 to 8.2 ft)
Carrier Smoothed C/A Code Phase with High Accuracy External Differential Corrections	L1 Only	0.2 m to 1.0 m (0.6 ft to 3.3 ft)
Carrier Smoothed C/A Code Phase (internally developed atmospheric corrections)	L1/L2 (or L5)	0.2 m to 1.0 m (7.2 in to 3.3 ft)
Carrier Phase RTK	L1, C/A	1.0 cm (0.4 in)

Source: ARINC April 2012

For many of the applications described above, a single frequency code phase differentially corrected receiver is sufficient.

For applications requiring high confidence levels at error radii below about 2 meters (6.6 feet) the problem becomes more challenging. Many of the high accuracy systems require external corrections or supplementary information (e.g., integer ambiguity), and many of these systems rely on long dwell times to achieve high levels of accuracy. Long dwell times are obviously incompatible with a mobile system and the use of a fixed station to either provide differential corrections or integer ambiguity data requires wireless systems that are expensive to operate and maintain, and this constrains the availability of this information and thus the areas where the system can provide this level of accuracy. These higher accuracy systems are examined in more detail below.

1.7.3 Deployability Assessment

1.7.3.1 RTK and Carrier Phase Systems

RTK and various carrier phase systems are commercially available from a variety of sources, and, as described above, they provide outstanding accuracy. The primary issue with these systems is the need for a base station and a communications link capable of providing correction information to the “rover” unit. This approach is impractical for an automotive system simply because it the vehicle will quickly move out of range of the base station. Obviously one can use longer range communications, but this too is somewhat problematic and can become expensive in a nationwide implementation.

The HA-NDGPS system has demonstrated that high accuracy (sub meter) carrier phase GPS is achievable at baselines up to about 120 miles (200 Km). The drawback to this approach is that it requires some means for communicating the correction information over these distances across the entire road network.

An alternative approach is to rely on code phase GPS on most open roads, and provide carrier phase information at intersections and other key locations where higher accuracy is needed. This could be accomplished relatively easily at intersections that are equipped with DSRC RSEs used to support connected vehicle applications. In this approach the RSE would include, or be connected to a carrier phase base station, and would transmit carrier phase corrections to be used by in-vehicle systems in the local area. Outside the intersection area, the vehicle systems would maintain carrier ambiguity information for some distance and at some point would revert to code phase positioning.

1.7.3.2 Carrier Smoothing Systems

Carrier smoothing systems have been deployed in various forms for over a decade. These systems typically also rely on externally derived differential corrections, although multi-channel systems are able to operate independently if they have sufficient dwell time to resolve the correction information. The primary drawback of these systems is the impact of the smoothing filter on the position estimates under dynamic roadway conditions. Because the filter has a finite loop response, it will, in the absence of any additional dynamic information, assume that the vehicle is continuing in the direction it was last traveling. At higher speeds and under complex maneuvers or on winding roads, the filtered results may tend to lag the position of the vehicle when it changes direction.

It is, of course possible to improve the filtering to account for vehicle dynamic behavior. This would require the introduction of other measured parameters such as yaw and acceleration into the trajectory prediction elements of the filter, but it would presumably allow the filter to more accurately predict and track the trajectory under dynamic situations.

1.7.3.3 Differential Corrections

The use of differential corrections is generally assumed in GPS systems. These corrections are provided by a network of continuously operating reference stations (CORS) that is managed by a large number of different organizations [12]. In part because of the large number of CORS participants and stations, and in part because of the availability of the competing WAAS system, ongoing funding for the system is always under scrutiny, particularly the higher accuracy National Differential GPS stations operated by the US DOT.

For real-time applications, the primary alternatives to NDGPS are the Federal Aviation Administration’s Wide Area Augmentation System (WAAS) and commercial augmentation systems. In areas of clear sky coverage, these systems can provide equivalent performance to NDGPS. However, the fact that they use the same downlink as GPS, anytime a GPS signal is lost the corresponding WAAS signal from the satellite is also lost. There are more WAAS-equipped receivers in the field than NDGPS receivers, which can primarily be attributed to the fact that it can provide good performance for aviation and for recreational users who are typically operating, for example, out on the water where there are few obstructions to disrupt the signals. In contrast NDGPS users typically have requirements for accurate navigation and positioning in all environments including wilderness areas, areas with topographical influences, and areas of heavy terrain or foliage which is problematic for line of sight correction delivery systems such as WAAS.

1.7.4 Installation, Test and Calibration

There are no tests or calibration issues for GPS based systems. In general, the primary issue for vehicle installation is that the GPS antenna must have a clear view of the sky, and this requires that the antenna be mounted to the roof of the vehicle. This problem has generally been solved by the automotive industry to support vehicle navigation systems. Examples of production GPS antenna installations are provided in Figure 1.7-8 below.

Figure 1.7-8. Commercial Automotive GPS Antennas
(Source: Automotive Manufacturers' Product Literature)

1.7.5 Applicable Standards

GPS is governed by a variety of standards. Not all of these are applicable to GPS Receivers, at least within the basic specifications of the GPS system. Relevant standards include:

- The Radio Technical Commission for Maritime Services (RTCM) is an international non-profit scientific, professional and educational organization. RTCM Special Committee (SC) 104 on Differential Global Navigation Satellite Systems (DGNSS) provides standards that are often used in Differential GPS and Real Time Kinematic operations
- National Marine Maritime Electronics Association (NMEA) specification 0183 is a combined electrical and data specification for communication between marine electronic devices including GPS receivers and many other types of instruments. The NMEA 0183 standard uses a simple ASCII, serial communications protocol that defines how data is transmitted in a "sentence" from one "talker" to multiple "listeners" at a time. Through the use of intermediate expanders, a talker can have a unidirectional conversation with a nearly unlimited number of listeners, and using multiplexers, multiple sensors can talk to a single computer port.

1.7.6 Cost and Life Cycle Status

GPS Receivers exhibit a wide variation in cost, depending on the type and application. Table 1.7-2 provides a breakdown of typical prices for the main types of receivers (receivers only, not navigation systems). Prices for embedded OEM components are generally lower.

Table 1.7-2. GPS Receiver Price Comparison

Position Detection Approach	Signals Used	Price Range ($)
C/A Code Phase Only	L1 Only	$30-$70
C/A Code Phase Only with External Differential Corrections (WAAS)	L1 Only	$250-$350
C/A Code Phase Only (internally developed atmospheric corrections)	L1/L2 (or L5)	N/A
Carrier Smoothed C/A Code Phase	L1 Only	N/A
Carrier Smoothed C/A Code Phase (internally developed atmospheric corrections)	L1/L2 (or L5)	N/A
Carrier Phase RTK Rover	L1/L2	$2K-$15K
Carrier Phase RTK Rover/Base Set	L1/L2	$15K-$100K

Source: ARINC April 2012

The table illustrates the substantial gap between the high and low-end receivers. Generally, low end receivers range from $30 to about $350, with the higher end of this group including WAAS and Differential correction capability. There appears to be no middle ground in the market. The next step in performance is to go to carrier phase units that are able to support multiple frequency channels (typically L1/L2), and can support RTK (usually with the addition of other components). The lowest end of these devices sells for around $2K. RTK base units with a corresponding rover begin at around $30K and go up from there.

This gap appears to be primarily a result of market pressures. The lower end of the spectrum is aimed at consumer applications that do not require extreme accuracy (recreational use, navigation, etc.). The higher end is dominated by professional survey equipment. We were unable to find any devices advertised as multiple frequency receivers that were not also able to support carrier phase and RTK.

There is no inherent reason that a multiple frequency receiver should cost 10 times the cost of a single frequency receiver. For example, the L2C signal is slightly lower in frequency, and so technologically, receiving this signal should be no more difficult than receiving the L1 signal. Discussions with receiver manufacturers indicate that the main reason higher end receivers are so much more expensive is that they are aimed at a professional market that demands rugged systems that can deliver the highest possible performance, and the market is smaller, so the costs of development are amortized over fewer units.

1.7.7 Technology Evolution and Forecast

There are ongoing efforts to improve the GPS system. In 2000, U.S. Congress authorized a modernization effort, referred to as GPS III. The project involves new ground stations and new satellites, with additional navigation signals for both civilian and military users, and aims to improve the accuracy and availability for all users.

One of the first announcements was the addition of a new civilian-use signal to be transmitted on a frequency other than the L1 frequency used for the existing C/A signal. Ultimately, this became known as the L2C signal because it is broadcast on the L2 frequency (1227.6 MHz). The L2C signal is tasked with providing improved accuracy of navigation, providing an easy-to-track signal, and acting as a redundant signal in case of localized interference.

L2C contains two distinct PRN sequences:

- CM (for Civilian Moderate length code) is 10,230 bits in length, repeating every 20 milliseconds
- CL (for Civilian Long length code) is 767,250 bits, repeating every 1500 milliseconds (i.e., every 1.5 s).

Safety of Life is a civilian-use signal, broadcast on the L5 frequency (1176.45 MHz). The first GPS satellite with an L5 test payload was launched from Cape Canaveral on March 24, 2009. On April 10, 2009, the L5 test transmission was turned on by the GPS Control Segment. The first GPS block IIF satellite, launched on May 28, 2010, continuously broadcast the L5 signal starting on June 28, 2010.

The L5 signal improves signal structure for enhanced performance. I t has higher transmission power than L1 or L2C signal (~3dB, or twice as powerful), and wider bandwidth, yielding a 10-times processing gain. It also has a longer spreading codes (10 times longer than used on the C/A code), which should improve accuracy.

1.1.1.1 New Civilian L1 (L1C)

L1C is a civilian-use signal, to be broadcast on the same L1 frequency (1575.42 MHz) that currently contains the C/A signal used by all current GPS users. The L1C will be available with first Block III launch, currently scheduled for 2013 and:

- Implementation will provide C/A code to ensure backward compatibility;
- Assured of 1.5 dB increase in minimum C/A code power to mitigate any noise floor increase;
- Non-data signal component contains a pilot carrier to improve tracking.

1.7.8 GPS References

Table 1.7-3. GPS References

[1] Hernandez-Pajares, M., et al, "Wide-Area RTK, High Precision Positioning on a Continental Scale", Inside GNSS, March/April, 2010.
[2] Takasu, T. and Yasuda, A., "Kalman-Filter-Based Integer Ambiguity Resolution Strategy for Long-Baseline RTK with Ionosphere and Troposphere Estimation", Proceedings of the ION GNSS 2010, September 2010.
[3] Henkel, P. and Gunther, C., "Reliable Integer Ambiguity Resolution with Multi-Frequency Code Carrier Linear Combinations", Proceedings of the ION GNSS 2010, September 2010.
[4] "AdVance RTK – Competitive Analysis", D14952, Novatel.com.
[5] Phillips, M.R., et al, "High Performance RTK for Small UAVs", Proceedings of the ION GNSS 2010, September 2010.
[6] Dai, L., Han, S., Wang, L., Rizos, C., "A Study on GPS/GLONASS Multiple Reference Station Techniques for Precise Real-Time Carrier Phase-Based Positioning", Proceedings of the ION GPS 2001, September 2001.
[7] Fotopoulos, G., Cannon, M.E., "An Overview of Multiple-Reference Station Methods for cm-Level Positioning", GPS Solutions, Vol. 4, No. 3, 2001.
[8] Improving Positional Accuracy Using Carrier Smoothing Techniques In Inexpensive GPS Receivers; Sudha Neelima Thipparthi. A thesis submitted to the Graduate School in partial fulfillment of the requirements for the Degree Master of Science in Electrical Engineering New Mexico State University, February 2004
[9] Performance Analysis of Position-Domain Hatch Filter; Hyung Keun Lee and Chris Rizos, Published by SNAP, University of New South Wales [http://www.gmat.unsw.edu.au/snap/publications/leehy_etal2003d.pdf]
[10] Carrier-Phase DGPS System Accuracy Tests: Increasing Baseline Distance and Using CORS Network Data; J. Booth, T. Lunde; Proceedings of the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS/GNSS 2003), September 9 - 12, 2003

[11] http://webone.novatel.ca/assets/Documents/Bulletins/apn014.pdf	
[12] NDGPS Assessment Report; Gary Pruitt, ARINC Incorporated, Carl Eric Fly, SEAM Prepared under contract No. DTFH61-04-D-00002	

Source: ARINC April 2012

1.8 Digital TV Ranging

1.8.1 Overview of Digital TV Ranging Technology

GPS technology has evolved and improved significantly in recent years thanks to the development of many mass-market applications, such as car navigation, asset management or mobile positioning. Unfortunately, in difficult environments such as dense urban or indoor areas, GPS shows limited accuracy and availability due to masking, multipath reflections and/or diffraction of the direct signal. This compromises the use of GPS as a standalone mean for robust positioning in these challenging environments. Urban areas, however, have the advantage of including telecommunication networks to provide users with various types of wireless services including mobile phone, and digital television services. It is possible to use these “signals of opportunity” to supplement, and in some cases replace GPS signals.

When a digital television is turned on, it receives a number of TV signals from different channels, as illustrated in Figure 1.8-1. So it first tunes into a channel (a specific frequency) and receives a stream of images transmitted from a TV tower. To receive these images (and audio), the television synchronizes itself with the transmitter based synchronization segments embedded in the digital data stream

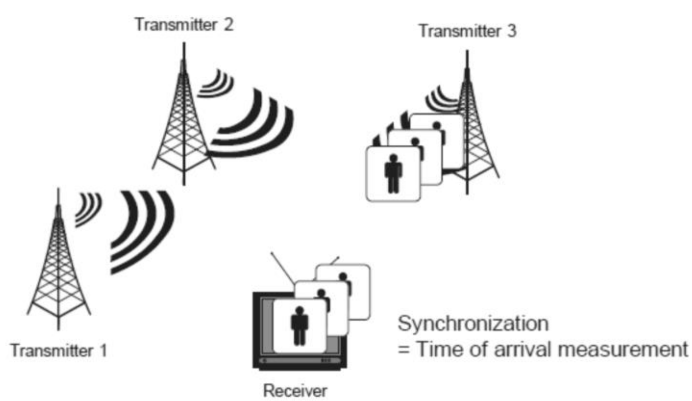


Figure 1.8-1. Broadcasting Television and Signal Reception
Source: ARINC April 2012

The synchronization process involves correlation of Pseudorandom Noise (PRN) sequences in a way that is similar to the way a GPS receiver uses C/A code sequences to determine the time synchronization of the GPS signals. The time of the correlation peak corresponds to the time of arrival (TOA) of signals. These TOA measurements can be used for positioning after removal of transmitter clock biases.

However, the information received by an individual TV receiver is not sufficient to properly calibrate the clocks. For the clock calibration (removal of clock biases), an additional supportive component, a Monitor Station, is used to collect independent TOA measurements and generate clock calibration information. This is illustrated in Figure 1.8-2. A group of Monitor Stations constantly detects, and computes the clock calibration information, then sends the aggregated data to a Position Server, which can then provide a collective set of calibration data. The information flow between a vehicle/user device and a monitor station is illustrated in Figure 1.8-3 below.

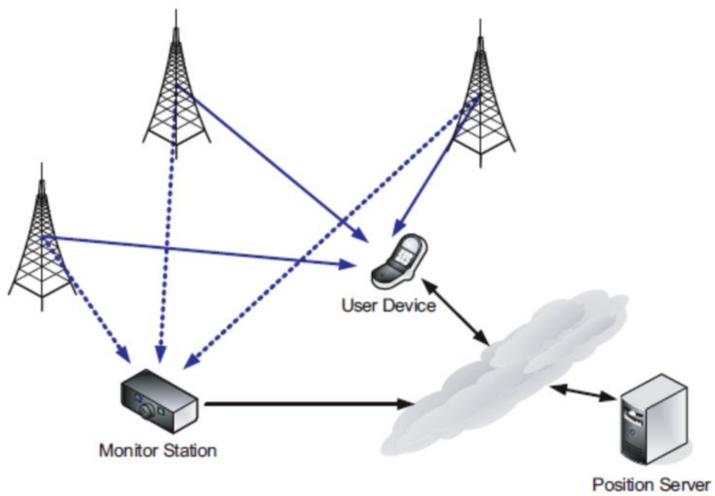


Figure 1.8-2. Television Signals for Radio Positioning
Source: ARINC April 2012

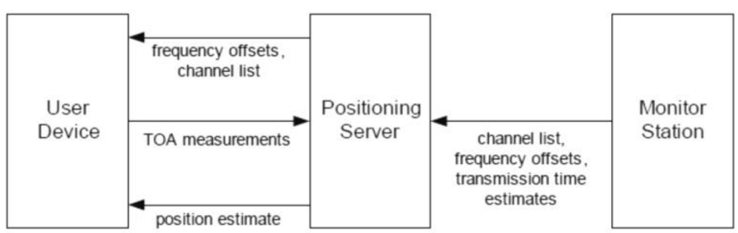


Figure 1.8-3. TV Positioning System Flow Diagram
Source: ARINC April 2012

Because of the relatively small geographic distribution of television transmission towers, this system is not generally used by itself. Instead, the television signals are used as supplementary pseudoranges to augment the GPS signals that are available. This hybrid system is shown below in Figure 1.8-4.

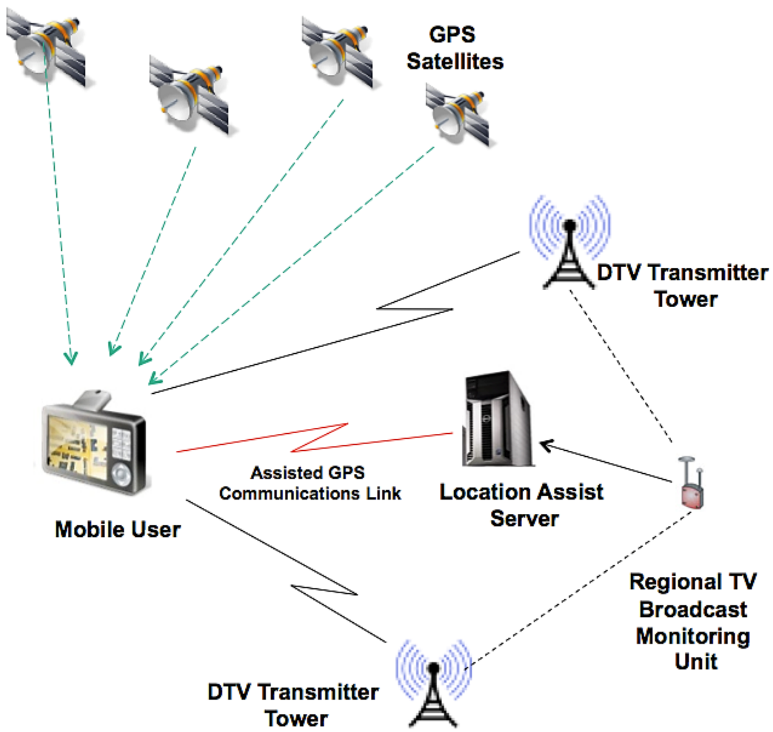


Figure 1.8-4. Mobile User Location Determination Using Terrestrial Digital TV Broadcast Signals
Source: ARINC April 2012

Figure 1.8-6 illustrates a typical in-vehicle unit block diagram. This system includes a GPS receiver, a digital TV receiver and a digital data link. The GPS receiver collects GPS pseudoranges using conventional C/A code offset correlation, and also provides an accurate time base for the digital TV receiver. The digital TV receiver collects the ranging information for the various transmission towers, and a wireless data link provides a connection to the Position Server to provide calibration information. The GPS and TV pseudoranges are then used in a conventional least squares computation to determine an estimated position for the receiver. The position estimation can be done either at the vehicle/user device or the pseudoranges can be sent over the data link to the position server, and the computed position estimate can then be sent back to the vehicle system.

Figure 1.8-5. Digital TV Supplemented GPS Positioning System In-Vehicle Unit Block Diagram

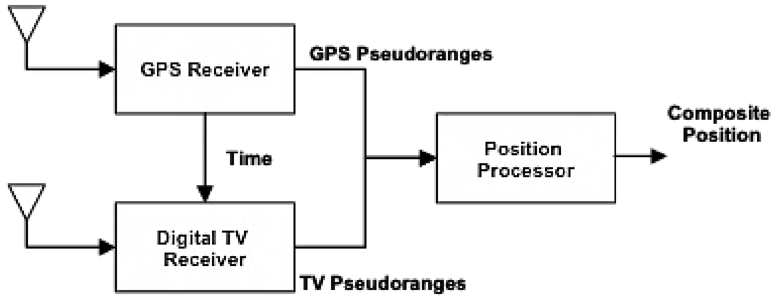


Figure 1.8-6. Digital TV Supplemented GPS Positioning System In-Vehicle Unit Block Diagram
Source: ARINC April 2012

1.8.2 Digital TV Ranging Performance Assessment

Research indicates that pseudoranges with accuracies of less than 1 meter are achievable with a slight degradation in the presence of strong multipath [1], [2].

However, this system is subject to a variety of other performance limitations. In correspondence (03-11-2011) with Dr. Oliver Julien of Ecole National de l' Aviation Civil (ENAC), Toulouse, France who has been researching GPS/TV for the last 4 years, he states: "Considering the large bandwidth and the high power of DTV signals, the tracking accuracy capability can be very good when the transmitter is in clear view (about 10 centimeters of standard deviation error for a 8 MHz bandwidth @ a 5 dB SNR, fixed and not accounting for pseudo range bias). Of course, when considering the impact of a terrestrial channel (loss of direct signal, multipath, changing conditions, etc.), the performance can be much degraded since it is likely to not track the direct signal. Our first results on real signals show a pseudo range error standard deviation of a few tens of meters in an urban environment, but this still needs to be confirmed more extensively. The main problem with using DTV signals is the propagation channel. Because the transmitters are on the ground, it is very common that the direct signal is blocked, or that strong multipath affects the reception (refraction, reflections, etc.). Consequently, even if all the transmitters' clocks are synchronized with GPS time, there will still be strong errors in the pseudo range measurements. From what we have seen, in an open sky environment, the pseudo range accuracy could indeed be at the decimeter level. However, in an urban environment, it can go up to tens of meters. It gets more difficult in dynamic scenarios where conditions change very fast. We are currently investigating ways to improve this through more "advanced" signal processing. "

Results reported by Rosum Corp. [3], indicate a 65 m/95% outdoor positioning accuracy. Other research [4] by the same author showed results of 5 m/67% accuracy for outdoor testing, so the factors governing accuracy do not appear to be under control.

One benefit of TV pseudo ranging is identified in a research paper entitled, "Multi-Fault Tolerant RAIM Algorithm for Hybrid GPS/TV Positioning" (Ref: [124]), performed by Stanford University, indicated that using this approach availability was significantly improved, but location accuracy was not particularly good. This research is summarized in Table 1.8-1 below.

Table 1.8-1. Results of Research on GPS/TV Positioning Conducted at Stanford University

Position Source	Availability	Position Accuracy 95%
GPS	84%	47 m
TV	80.4%	353 m
Hybrid (GPS/TV)	95.7%	375 m

Source: ARINC April 2012

The conclusion is that the while the digital TV supplemental ranging approach does improve availability, it does not provide sufficient positioning accuracy to be useful for any of the applications considered.

In addition the use of the assisted communications link back to a support server (similar to that utilized by cellular communications service providers) has latency of several seconds and this is also is incompatible with most ITS positioning needs.

1.8.3 Deployability Assessment

This technology is emerging, and based on third party testing, provides an augmentation to GPS positioning when satellite geometry and masking reduces the availability of GPS alone.

While the technology does not appear to be viable for e911 or other ITS applications, several companies appear to be using this approach in the asset tracking market, so it is being used to some degree. One manufacturer has patented an approach of using digital television OFDM modulation to extract pseudo range, supporting augmentation of GPS. They offer a chip called ALLOY, which can be utilized in cellular telephones.

The technology does rely on geometry of television station transmission tower deployment within a region. As television broadcasting towers and infrastructure are maintained by each operator, there is no specific cost and supportability involved from the US DOT's perspective. However, it is also unclear if there is any motivation for the digital TV broadcasters to provide or maintain any of the supporting services and equipment, and it is unclear how liability for the use of these signals for safety systems would be managed.

The pros and cons of this technology are summarized in Table 1.8-2.

Table 1.8-2. Pros and Cons of TV Transmitter Tower Pseudo Ranging and GPS Augmentation as Evaluated by the Locata Corp.
(Ref: "Technology Primer", Locata Corporation, Feb. 2009 [91])

Pros	Cons
• Strong signal; • DTV already deployed; • Wide area coverage; • Low cost maintenance of infrastructure conducted by TV station routine maintenance.	• Not currently designed for accurate ranging; • Not geographically disperse. Deployment geometry not necessarily optimum; • Clock utilized not highly accurate and stable; • No clock synchronization between emitters (non-mobile configurations); • Requires reference receivers to correct clock errors; • Non-mobile ATSC signals not designed for mobile applications; • Requires a communications link to function; • Requires TV receivers/processor in mobile devices; • significant multipath; • Tower deployment geometry may not be optimum to maximize performance and requires partnership support of TV Station owners to modify existing transmission stations. Must solve multipath signal distortion issue. Also limited or no TV towers in rural areas; • Low cost deployment. Requires a modified chip designed for direct pseudo ringing from TV signals (not assisted GPS).

1.8.4 Installation, Test and Calibration

The in-vehicle device is self-calibrating, and so there are no installation, test or calibration requirements other than the basic need for a clear view of the open sky.

1.8.5 Applicable Standards

Digital TV ranging relies on the ATSC Standard developed by the Advanced Television Systems Committee for digital television transmission over terrestrial, cable, and satellite networks.

The ATSC standard was developed in the early 1990s by a consortium of electronics and telecommunications companies that assembled to develop a specification for what is now known as HDTV. ATSC formats also include standard-definition formats, although initially only HDTV services were launched in the digital format. The specific approach of ranging on the digital TV signals depends on the ATSC Mobile DTV standard ATSC-M/H.

1.8.6 Cost and Life Cycle Status

Technology Status in USA:

> Chip available supporting ATSC TV signal reception and pseudo range calculations; requires separate infrastructure to support TV sync signal clock correction. Not proven in a high mobility environment.

Technology Status in Europe and Asia:

Use OFDM Modulation and Single Frequency Network with GPS Time Sync. Test indicates potential of < 1 m position accuracy in a static environment and tens of meters in a high multipath environment, typical of urban environments. Research continues to accommodate multipath.

1.8.7 Technology Evolution and Forecast

The lack of time synchronization in the ATCS standard adds complexity (requiring the position server calibrations) and limits the overall accuracy of the system. The European single frequency network (SFN) approach includes GPS time synchronization of clocks in all distributed transmitter stations, so this system is possible candidate to support mobile vehicle pseudo ranging from TV transmitter towers. SFN is an approved standard in Europe and other countries, but it is not currently in the ATSC standard.

Evolution of mobile TV in the US should be monitored because, by using high accuracy, GPS synchronized clocks, pseudo ranging could be accomplished without the TV monitoring stations, clock error corrections and assisted data link. Clock upgrades, considering that a GPS high accuracy clock chip is relatively inexpensive, would be an affordable upgrade for TV stations. Also, since chips that support multiple TV channel reception are available, only modifications to the algorithms associated the clock signal processing would be required to be made.

1.9 RADAR Systems

1.9.1 Overview of RADAR Technology

Radio Detection and Ranging (RADAR) technology can be used to support vehicle detection and positioning for both vehicle and infrastructure systems. Figure 1.9-1 illustrates RADAR products either deployed or in a test status that are advertised by major sensor manufacturers.

RADARs sense targets by illuminating them with radio waves, and then sensing the time, direction, and in some cases frequency of the reflected “radar return” signals. The time and direction provide range and direction, while the frequency shift can be used to measure relative speed. The level of the radar return signals can vary depending on the size, shape and material of the target. Discriminating moving targets from fixed targets and targets of no interest (known as clutter) requires significant signal processing. In high clutter environments false positive and false negative detection errors are common.

Infrastructure related RADAR is currently deployed to essentially emulate inductive loop applications such as detecting vehicles at specific locations on a corridor as determined by location of the beam pattern on the corridor and providing vehicle presence, count, headway, length classification and speed (using dual beam) the signal controller and the traffic management center (TMC). The deployed RADAR sensors generate calls to signal controllers, as well as providing traffic statistics to the TMC.

Vehicle on-board equipment RADAR is designed to provide range and azimuth (relative to the host vehicle) of fixed and moving objects considered to be a potential safety threat to the vehicle. Vehicle RADAR supports functions such as automated driver assist, autonomous cruise control, blind spot driver awareness, collision avoidance, and similar functions. In general, vehicle RADARs are designed to provide higher accuracy measurements compared with infrastructure RADAR, and they may include target tracking and sensor fusion technology. Vehicle RADARs also typically exceed the environmental requirements of infrastructure RADAR (temperature, humidity, shock, and vibration). Vehicle RADAR requires a GPS/IMU signal to support stabilization and target tracking. This data is generally acquired form a CAN bus interface.

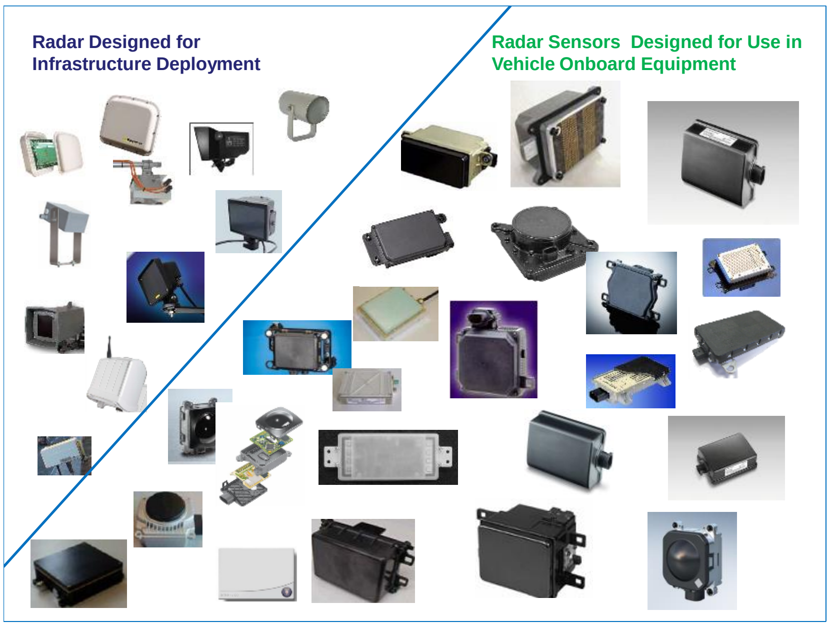


Figure 1.9-1. Examples of RADAR Equipment Designed for Infrastructure and Vehicle Onboard Equipment Deployment
(Source: Composite from Various RADAR Manufacturers' Product Literature)

RADARs are of three basic types: Pulse Doppler, Ultrawideband, and FMCW.

Pulse Doppler RADARs transmit a short pulse and measure the time required for the pulse to travel to, and reflect back from various objects in the field of view. The Doppler frequency shift of the return signal, caused by the motion of the object toward or away from the RADAR, is measured to estimate the relative speed of the object. It is important to note that in a complex roadway environment, objects may be moving across the field of view of the RADAR, and these objects will indicate near zero relative speed. To eliminate background clutter of fixed objects that are not of interest, a velocity threshold is typically established. Targets are filtered if they do not exceed the filtered speed.

Ultrawideband RADARs operate in a manner similar to pulse Doppler RADARs except that instead of transmitting a short burst of carrier energy, they use a very short pulse that emulates a delta function in time. This pulse generates very wide frequency, but very low-level spectrum. Because the pulses are so short (nanoseconds), it is possible to resolve very fine range differences. Because there is no carrier per se, the UWB RADAR does not resolve any Doppler shift. Speed information is detected as range rate. Because of the relatively short range, UWB RADAR are typically not used except for near field proximity sensing, although in these applications ultrasonic and infrared systems are often lower cost and simpler solutions. Long range UWB RADAR is available for military applications but is not available for commercial applications due to FCC emissions standards for commercially available frequency bands.

FMCW RADAR uses a continuous signal that is linearly modulated in frequency. The transmitted signal (called a “chirp” since it is changing in frequency) reflects off objects in the field of view and the return signal is compared to the currently transmitted signal. Since the frequency is changing linearly over time, the difference in frequency between the currently transmitted signal and the received return signal represents the round trip propagation time, and thus represents the range to the object. This is illustrated in Figure 1.9-2 . Unlike pulse Doppler RADARs, FMCW RADARs cannot directly measure the speed of the object (instead they measure the change in range over time, i.e. range rate), but because the signal propagation times for close by objects can be very small, pulse Doppler RADARs are less effective for detecting and measuring nearby objects, and their range resolution is limited by the ability to discriminate small differences in time. RADAR signals travel at the speed of light, so a resolution of one foot (0.3 meters) requires resolving a difference in time of one nanosecond. In contrast, the FMCW RADAR range resolution depends on the frequency slope of the FM chirp, and the ability to resolve differences in the frequency of signals, which is a much more controllable, process that is less susceptible to noise.

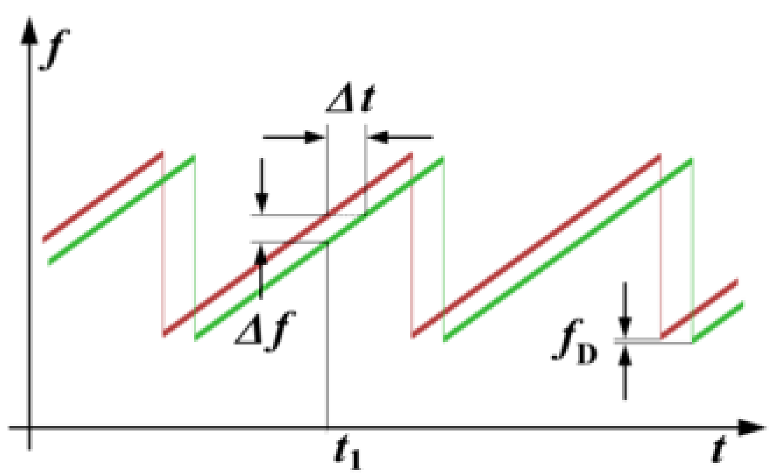


Figure 1.9-2. FMCW RADAR Wave Form
(Ref. “Continuous Wave Radar, Wikipedia, 2011 [99])

Using FMCW RADAR, the range of the object can be determined as follows:

$k = \Delta f_{RADAR} / \Delta t_{RADAR}$,

where f_{RADAR} = the RADAR sweep magnitude, and

t_{RADAR} = the sweep time.

Then, $\Delta f_{echo} = t_r k$,

and then

$t_r = \Delta f_{echo} / k$

where t_r is the round trip travel time of the transmitted signal.

Range of the target = $dist_{one\text{-}way} = ct_r/2$

where c = speed of light.

In order to resolve position, the RADAR must measure both range and azimuth. The combination of these parameters then provides the position of the object relative to the position of the antenna. RADAR inherently measures range; to obtain azimuth, the RADAR signal must be formed into a relatively narrow beam. The beam width thus determines the angular (azimuth) resolution. There are physical constraints to what can be achieved relative to beam width, since narrower beams with low level side lobes requires larger apertures.

Depending on the application, the beam may be fixed, or scanned. Fixed beam RADARs are able to determine if an object is in a particular angular sector defined by the angular width of the beam. These systems are generally used to sense the presence of a vehicle in some location, for example, at a particular intersection. In this case the system uses what is known as a “range gate” to select RADAR signal returns coming from a specified range (and obviously within the beam). If presence in a particular lane, for example, is needed, the system must be configured (range gate and beam width) to look for RADAR returns originating from that defined location. This is illustrated in Figure 1.9-3 below.

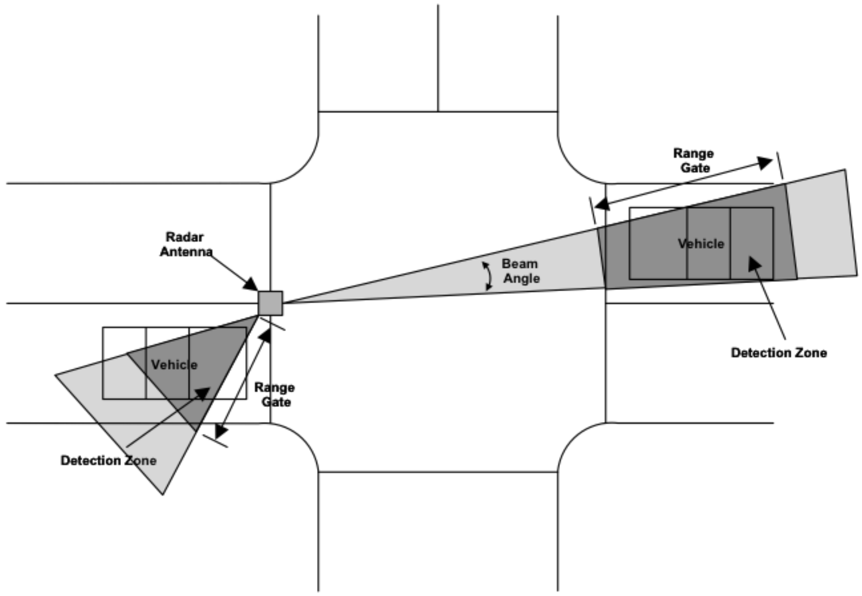


Figure 1.9-3 Use of Range Gates to Detect Vehicles at Specified Locations
Source: ARINC April 2012

Other ways to determine azimuth include scanned beam, and monopulse systems. Scanned beam system use a narrow beam that is mechanically or electrically scanned over a region in order to determine azimuth. The width of the beam determines the angular resolution. A scanned RADAR correlates the RADAR returns over a specific scan angle to effectively create azimuth and range gates that form a position coordinate system. The positional accuracy of a scanned system depends on the range resolution, the beam width, and the coordination between the RADAR signal time base and the scanning time base. Since the range is a function of the time of flight, the range position of the object is determined by a time difference between the originally transmitted RADAR signal and the signal return. Because the system is scanning, however, it is essentially looking at different azimuth segments at different times, so any error in the timing between the RADAR signal itself and the scanning mechanism will be observed as a lateral (azimuth) position shift. In general, the speed of light is so fast that the time required to scan the beam is sufficient to allow the system to collect RADAR returns over a long range before the beam has moved sufficiently off axis that the returns of a particular object are lost. However, since scanning is often done mechanically (by physically rotating or sweeping the antenna structure), scanned systems can suffer some latency (any given position is sensed only once per cycle), although other than mechanical structure limitations, reasonably high scanning speeds are possible. Electrically scanned systems generally use a phased array antenna where the overall antenna beam is formed from many small antenna elements. By adjusting the relative phase of the signals from each of the antenna elements, the signals from each antenna element will interfere with the signals from other elements, and this constructive and destructive interference forms the antenna pattern. By changing these phase offsets dynamically, the pattern can be changed causing the resulting beam to scan to region of interest.

Scanning RADARs generally have higher accuracy at shorter ranges because the beam has a finite angular width. A one degree beam can theoretically resolve about 1.7 meters at 100 meter range, but this same beam will be 17 meters wide at 1 km. New manufacturing techniques are supporting a reduction in cost of electronically scanned RADAR sensors, allowing this technology to be considered for vehicle applications.

A monopulse RADAR uses a different method to measure azimuth. A monopulse RADAR uses two antennas that are aimed in the same direction. One antenna, known as the “sum” antenna, has a conventional beam with its sensitivity peak on the bore-sight of the antenna. The other antenna, known as the “difference” antenna, has a null on bore-sight. RADAR signals received on one side of the null have the same phase as the sum antenna, and signals received on the other side of the null have the opposite phase. The RADAR signal is transmitted using the sum antenna, and the RADAR returns are received using both the sum and difference antennas. By measuring the relative amplitude and phase the azimuth of the object can be determined with high accuracy. Monopulse RADARs have very high accuracy, and are used for missile tracking and other high precision systems. However, the high angular resolution means that the monopulse beam itself must be basically aimed at the object of interest (requiring some knowledge of the location of the object to begin with). Monopulse radars are currently used for vehicle applications.

The roadway environment has numerous objects that will return RADAR signals. These multiple objects create a type of noise known as clutter. Clutter creates false signal returns that may be sensed as objects of interest resulting in false alarms.

1.1.1.2 Vehicle Based RADAR Systems

Figure 1.9-4 illustrates a block diagram of a FMCW monopulse RADAR, and Figure 1.9-5 illustrates an implementation of the FMCW RADAR.

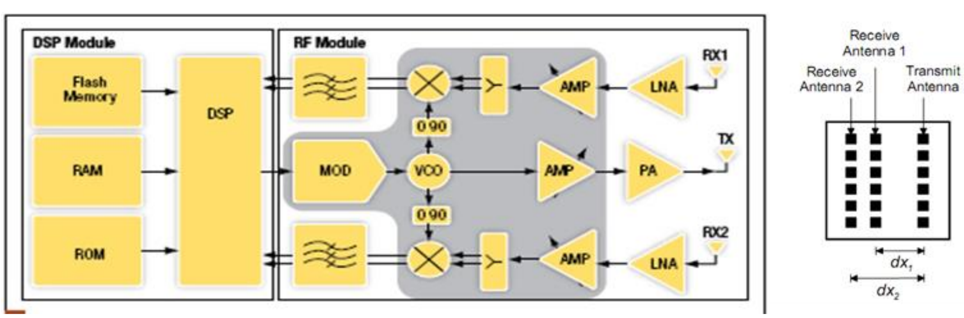


Figure 1.9-4. Block Diagram of an FMCW Monopulse RADAR for Vehicles
(Ref: “Products for Commercial Vehicles”, Wilfried Mehr, 6-25-09 [92])

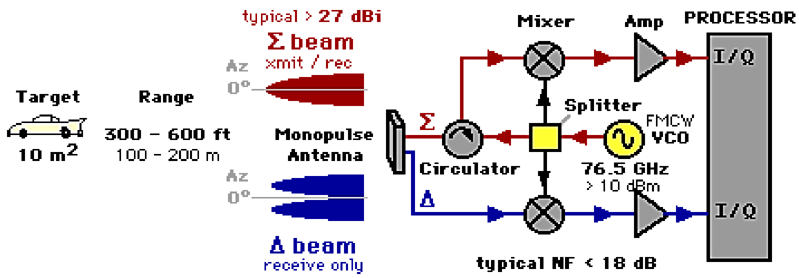


Figure 1.9-5. Illustration of FMCW RADAR Supporting Automated Driver Assist System
(Ref: COPAR Inc. RADAR Technical Product Data [93])

A typical active phased array antenna is composed of a two-dimensional array of "small antenna" elements, spaced a half wavelength apart. By use of phase shifters and attenuators, the radiated and received antenna patterns can be shaped and steered. The short wavelength of millimeter wave RADAR components has facilitated the development of small phased array antennas. Half wavelength of a 77 GHz signal is 1.9 mm as compared with 6.25 mm for a 24 GHz signal. Figure 1.9-6 through Figure 1.9-8 illustrate new RADAR technology available for vehicles.

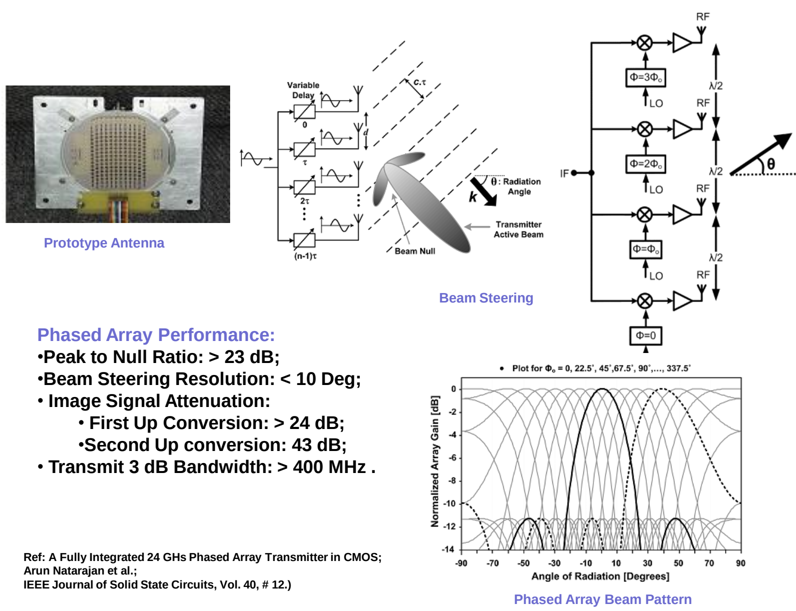


Figure 1.9-6. Example of a 24 GHz Phased Array Antenna
(Ref: Jan, A., et al, "A Fully Integrated 24 GHz Phased Array Transmitter in CMOS", *IEEE Journal of Solid State Circuits*, Volume 40, Number 12, 2005 [108])

Figure 1.9-7 illustrates a phased array RADAR utilized by Toyota, which is a variation of a single x,y array.

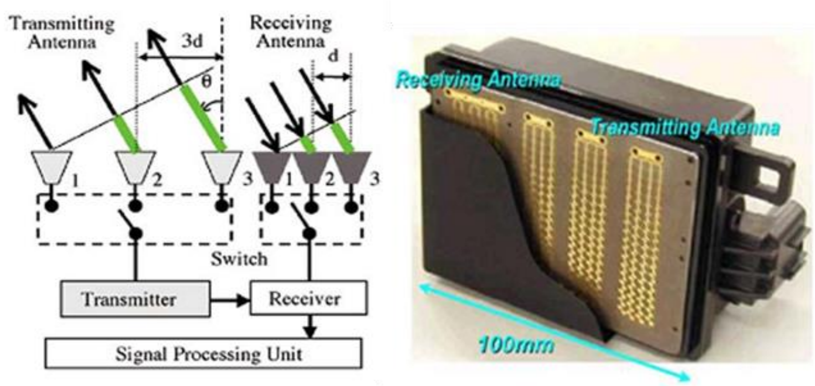


Figure 1.9-7. Example of a Three Element Transmitting and Receiving, 77 GHz Vehicle RADAR used by Toyota
(Ref: "Automotive RADAR – Status and Trends", Martin Schneider, Robert Bosch, Germany, 2005 [94])

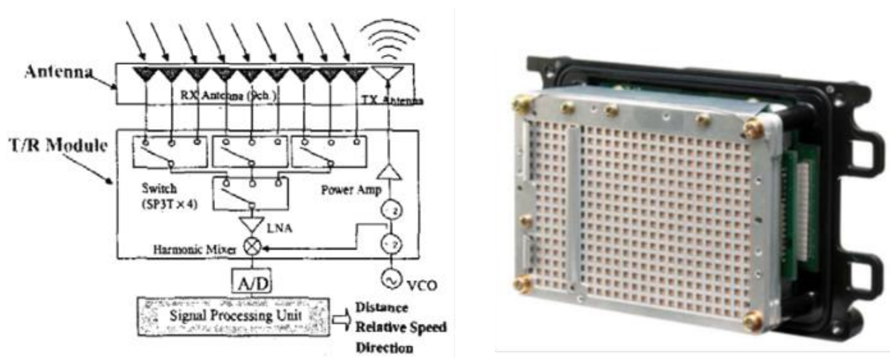


Figure 1.9-8. Example of a 77 GHZ Digital Beam Forming Vehicle RADAR
(Ref: "Automotive RADAR – Status and Trends", Martin Schneider, Robert Bosch, Germany, 2005 [94])

1.9.1.1 Infrastructure Based RADAR systems

Infrastructure RADARs are used primarily to either detect the presence of vehicles in particular lanes, or, in some cases to measure vehicle speed. Figure 1.9-9 and Figure 1.9-10 illustrate single and dual beam FMCW RADAR deployment. Range bins are used as described above to define detection zones. A vehicle entering into the detection zone is reported to a control device, which might, for example, change the signal timing cycle. Using dual detection zones allows the measurement of vehicle speed. Here the time between detection in one zone and detection in the next zone is used with the known distance between the two detection zones to determine speed.

Doppler RADAR can be used to more accurately measure vehicle speed since the Doppler shift of the radar signal is proportional to the speed of the vehicle.

Figure 1.9-11 illustrates masking of RADAR sensor's field of view by large vehicles, which typically results in under-counts of vehicles.

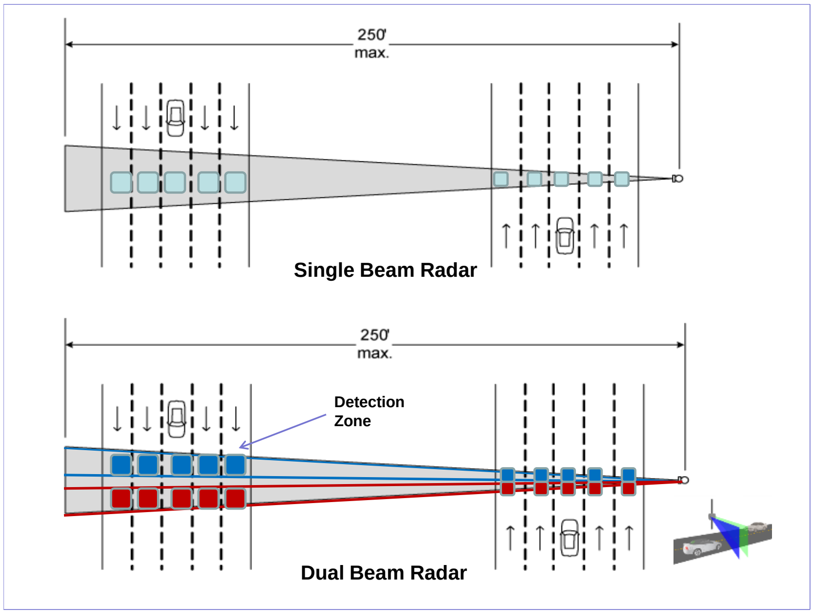


Figure 1.9-9. Example of Single and Dual Beam FMCW RADAR Deployment Supporting Infrastructure Vehicle Detection Applications
Source: ARINC April 2012

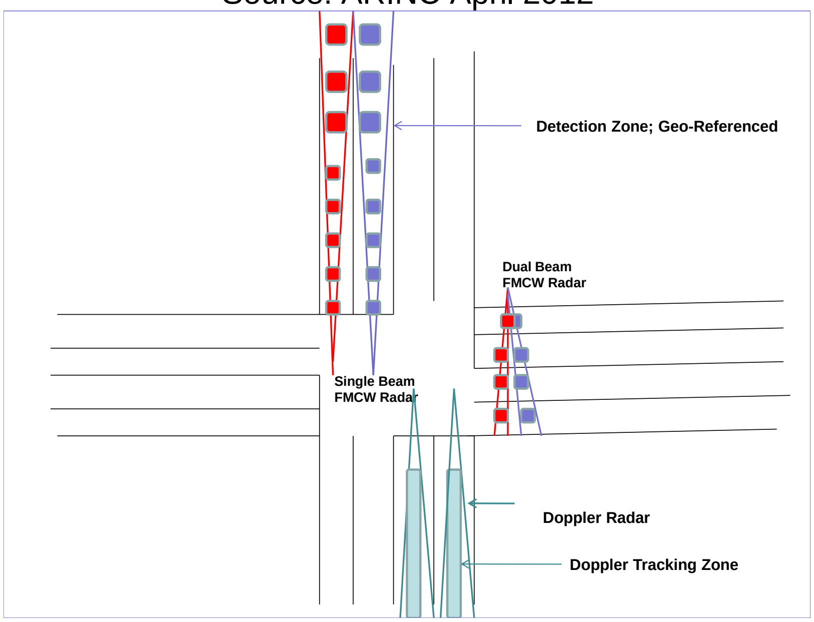


Figure 1.9-10. Example of Single and Dual Beam FMCW RADAR and Doppler RADAR Deployment Supporting Infrastructure Vehicle Detection at a Signalized Intersection
Source: ARINC April 2012

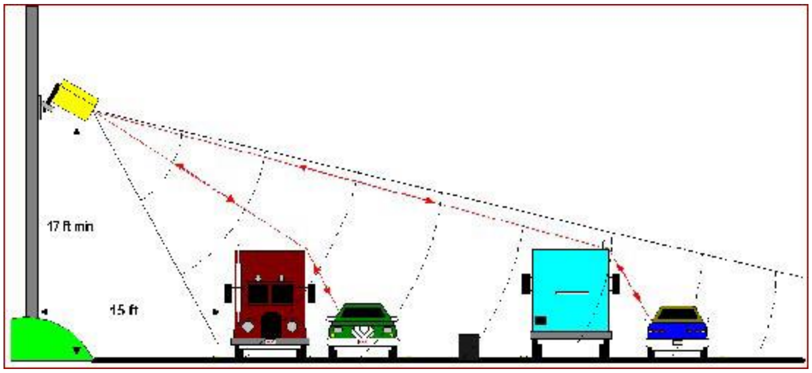


Figure 1.9-11. Examples of Large Vehicles Masking Smaller Vehicles
(Ref: Federal Highway Administration, Document FHWA-HRT-06-108; "Traffic Detector Handbook", October 2006 [95])

RADAR can support vehicle, bicycle and pedestrian safety applications at intersections and other safety applications where sub meter relative position accuracy is required within stopping distance of a location that has safety implications (such as a stop line).

Jurisdictional signal shops currently maintain infrastructure RADAR. The repair process is to remove and replace the RADAR. Board replacement may be accomplished in the signal shop or the complete RADAR unit returned to the manufacturer for repair. The RADAR is provided with software for laptop computers to facilitate set up and calibration of the RADAR. Detection zones may be geo-referenced where there is a need.

1.9.2 RADAR Performance Assessment

The following sections describe performance achievable for vehicle and infrastructure RADAR systems

Vehicle RADAR Performance

Table 1.9-1 presents a survey of vehicle RADAR and LIDAR products presented in the doctoral thesis by Flora Salim (Monash University, Australia; August 2008) entitled, "A Context-Aware Framework for Intersection Collision Avoidance" (Ref: [53]) (Note that manufacturer's names and model numbers have been removed).

To summarize, RADAR technology today is available with weight, size and power requirements suitable for vehicle applications. Vehicle RADAR is also available meeting the environmental requirements of cars and heavy vehicles. Some of the available products include signal processing to identify targets, extract velocity vectors and acceleration from changes in range and azimuth from scan to scan. A few of the available products include a target tracker; however, the trend is for a separate target tracker that includes a sensor fusion capability. Depending on the RADAR technology, pulse width, bandwidth, and beam forming technology used, today's vehicle RADAR technology can provide target ranging to 250 meters (820 ft.) with a 1% of range accuracy and an azimuth accuracy of 0.3 to 0.5 degrees. Scan rates available can provide updates on targets at an update rate of 40 to 50 milliseconds. While some of the short to medium range vehicle RADAR using nanosecond pulse widths and ultra wide band-widths can achieve 0.25 m (0.82 ft.) range accuracy, the long range RADAR tends to achieve a range accuracy of 2 to 3 meters (6.6 to 9.8 ft.). The multimode RADAR can change form a long range mode to a medium/short range mode increasing azimuth field of view and increasing range measurement accuracy; however, they generally sacrifice accuracy and resolution of the azimuth angle and/or scan time. The current relative position accuracy of RADAR sensors supports automatic driver assist systems (ADAS) relative position accuracy. The short range, UWB RADAR is capable of achieving the accuracy requirements of range, and with phased array (narrow beam) and fast scan can support perhaps a target revisit rate of 25 milliseconds and an azimuth angle measurement of < 1 degree. A vehicle with a closing velocity of 100 km/hr (63.1 mph) will have moved 0.7 meters (2.3 ft.) within the scan period.

Table 1.9-1. RADAR and LIDAR Devices
(Ref: Salim, F., "A Context-Aware Framework for Intersection Collision Avoidance", PhD Thesis, Monash University, Australia, August 2008 [96])

Product	Range	Separation Range	Relative Speed	Relative Acceleration	View Angle (H/V)
"Company A" Long Range RADAR Sensor	2 to 120 m	5 m	± 50 m/s	Not known	±8° / ±1.5°
"Company B" Adaptive Cruise Control RADAR System	1 to 150 m	7.5 m	-24.7 to 73.6 m/s (-89 to 265 km/h)	-20 to 20 m/s^2	±5.1° / ±1.7°
"Company C" Adaptive Cruise Control RADAR system	0.25 to 170 m	2 m	-24.7 to 73.6 m/s (-89 to 265 km/h)	-20 to 20 m/s^2	±9° / ±2.1°
"Company D" Side looking short range RADAR	0.2 to 30 m	0.2 m	-35 to 35 m/s (-127 to 127 km/h)	None	120° / 15°
"Company E" Closing velocity detecting short range LIDAR	10 m	Not Known	1 to 56 m/s (5 to 200 km/h)	Not Known	36° / 8°
"Company F" Short range LIDAR	0.5 to 50 m	Not Known	-60 to 60 m/s	Not Known	±15° / 3 to 6.5°
"Company G" LIDAR Sensor	0 to 130 m	Not Known	51 m/s	6.35 m/s^2	±18.0° / 4°
"Company H" RADAR Sensor	5 to 180 m	Not Known	-55.5 +27.8 m/s	6.35 m/s^2	±10° / 4°
"Company I" Long Range RADAR Sensor	1 to 150 m	Not Known	-63.9 to 31.9 m/s	Not Known	Not Known
"Company J" Short Range RADAR Sensor	0 to 6 m	Not Known	± 8.8 m/s	Not Known	Not Known
"Company K" Adaptive Cruise Control (LIDAR Sensor)	200 m	Not Known	±50 m/s	Not Known	16° / 3°
"Company L" 24 GHz Short Range RADAR	0.75 to 50 m	1.80 m	0 to 70 m/s	Not Known	±50 to ±70° / 13°
"Company M" LIDAR	0.3 to 80 m	0.5 to 1 m	Not Available	Not Available	240° / 3.2°
"Company N" Forward looking RADAR sensor	2 to 150 m	1.5 to 9 m	±50 m/s	Not Available	±18° / 4°
"Company O" Long Range RADAR Sensor	200m	0m	±50 m/s	Not Known	±6° / ±2.5°
"Company P" Multiple Beam RADAR	0.5 to 60 m	Not Known	0 to 69.4 m/s	Not Available	150° / Not Known

Source: ARINC April 2012

Table 1.9-2. Vehicle RADAR Specifications from Current Vehicle Data Sheets (NA = Not Available)

RADAR Specification Parameter	RADAR #1	RADAR #2	RADAR #3	RADAR #4	RADAR #5	RADAR #6	RADAR #7
Frequency	24 GHz	24 GHz	24 GHz	24 GHz	77 GHz Multimode	77 GHz Multimode	77 GHz
Bandwidth	1 GHz	500 MHz		500 MHz			15 MHz
Azimuth (3dB) Beam Width	± 30 deg.	±10 deg.	±6 deg.	±3.8, 6, 14 & 28 deg.	1 & 4 deg.		NA
Elevation Beam width (3dB)	±10 deg.	±10 deg.	±2 deg.	±2.5, 4, 5, & 5 deg.	4.3 deg.	4.2 to 4.75 deg.	4 deg.
Azimuth FOV	±30 deg.	±10 deg.	± 6 deg.	+-12, 18, 35, & 50 deg.	17 deg & 56 deg.	20 deg & 90 deg.	16 deg.
Azimuth Accuracy	NA	NA	0.5 deg.	0.5 deg.	0.1 deg (200 m range); 1-2 deg. (60 m range)	±0.3 deg & ±1 deg (90 deg FOV)	NA
Range	12 m (39.4') (Ped)	30 m (98.4')	180 m (590.6')	240, 160, 90, 45 m	2.5 to 200 m & 2.5 to 60 m	175 m 10 dB target & 60 m	1 to 120 m (3 to 300 ft)
Range Resolution	0.3 m (11.8")	0.3 m (11.8")	1 m (39.4")	0.5 m	2 m > 5.5 km/hr		NA
Range Accuracy	0.1 m (3.9")	0.1 m (3.9")	0.2 m (7.9")	+- 0.25 to 10 m/ ±2.5%	0.25 m or 1.5% > 1 m	2.5 m (175m) & 1.5 m (60 m)	+- 3%
Minimum-Maximum Velocity	NA	NA	NA	-70 to + 70 m/sec.	-88 to + 265 km/hr	-100 m/sec to + 40 m/sec	- 160 to + 160 km/hr (1 100 to + 100 mph)
Velocity Resolution	2.4 m/sec. (7.87 ft/sec)	2.4 m/sec. (7.87 ft/sec)	1 m/sec (3.3 ft/sec)	NA	2.76 km/hr (200 m range); 5.52 km/hr (60 m range)		NA
Velocity Accuracy	1 m/sec. (3.3 ft/sec)	1 m/sec. (3.3 ft/sec)	0.3 m/sec (0.98 ft/sec)	0.25 km/hr	0.5 km/hr (200 m range); 1 km/hr (60 m range)	+- 0.12 m/sec.	+- 1%
Targets Tracked	NA	NA	NA	32	NA	64	NA
Latency	NA	NA	NA	40 msec	66 msec	150 msec	NA

Source: ARINC April 2012

1.9.2.1 Infrastructure RADAR Performance

Current infrastructure RADAR is primarily designed to replace inductive loops at intersections and to support traffic statistics gathering on corridors. These systems are not designed to support collision avoidance.

It is reasonable to imagine that higher performance vehicle radar systems could be adapted to infrastructure applications, and these systems could support collision avoidance, vehicle tracking and other higher demand applications.

Performance specifications of infrastructure RADARs currently in use are summarized in Table 1.9-3 below.

Table 1.9-3. Specifications of Infrastructure RADARs Currently in Use (Taken from Published Data Sheets)

Parameter	RADAR #1	RADAR #2	RADAR #3	RADAR #3
Frequency	24 GHz (K Band)	24 GHz	24 GHz	24 GHz
Modulation	FMCW	FMCW	CW/Doppler	CW Doppler
Bandwidth	240 MHz		Not on Spec. Sheet	Not on Spec. Sheet
Azimuth 3dB Beam Width	7 deg.	12 deg.	Not on Spec. Sheet	Not on Spec. Sheet
Elevation 3 dB Beam Width	65 deg.	50 deg	Not on Spec. Sheet	Not on Spec. Sheet
Detection Zones	10	12	61 m x 15 m (200 x 50 ft) or 107m x 23m	1
Detection Zone Resolution	0.3 m (1 ft)	0.4 m (1.3 ft)	Not on Spec. Sheet	Not on Spec. Sheet
Detection Zone Width	NA	2-7 m (7-20 ft)	15 m (50 ft), 23 m (75 ft)	Not on Spec. Sheet
Detection Range	1.8 to 76.2 m (6 to 250 ft)	0.3 to 76 m (1 to 250 ft)	61 m (200 ft.) for car, 107 m (350 ft.) for truck	45 m (150 ft)
Time Resolution	2 msec	1.3 msec.	250 msec	1 sec
Vehicle Speed Range	N/A	N/A	0.62 to 100 mph	2.5 to 120 mph
Vehicle Speed Accuracy	+- 5 mph (8 km/hr)	N/A	3%	±1.9 mph to 62.1 mph
Occupancy (per Lane)	+-20%	N/A	3%	3%
Vehicle Classification	80% min; 90% Typical	6 (by length)	Not Applicable	Not Applicable
Headway	N/A	N/A	Not Applicable	Not Applicable
Vehicle Volume	N/A	N/A	Not Applicable	Not Applicable
Environmental	NEMA TS-2	NEMA TS-2	NEMA TS-2	Infrastructure RADAR #3
Size (H,W,D)	33.5 x 27 x 8.3 cm	21 x 21 x 16 cm	14 c 14 x 23.5 cm	80 x 160 x 100 mm
Weight	2.27 kg (5 lbs)	1.5 kg. (3.5 lbs)	2.27 kg (5 lbs)	1.5 kg (3.5 lbs)
Power	8 Watts, 9-28 VDC	3 Watts 12-24 VAC or VDC; Optional 115 VAC	2 Watts; 12-24 VDC	3.4 Watts; 10.5 to 30 VDC/ 24 VAC
Interface	EIA 232/485	EIA 232/485*	EIA 232	Relay

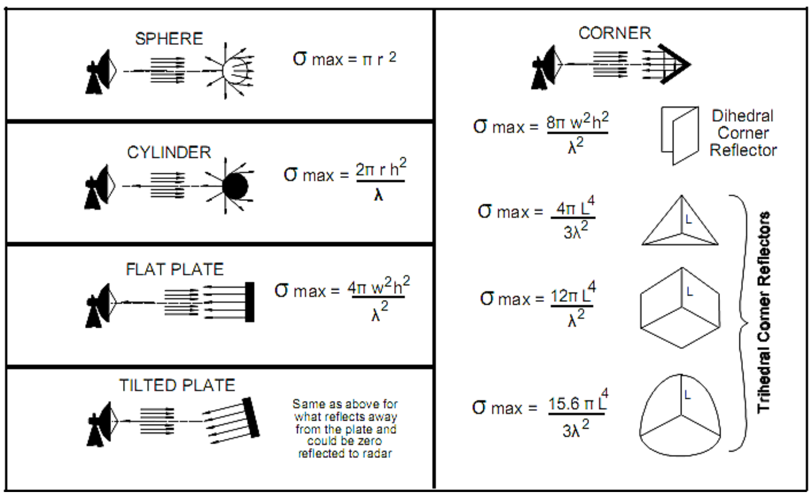
*Optional Wireless Ethernet with TCP/IP; NTCIP 1209 Protocol Option. Loop Detector Card for Traffic Controller (TS1, TS2, and 179 types)

Source: ARINC April 2012

1.9.2.2 General RADAR Performance Issues

The strength of the radar return signal depends on the effective size of the target being sensed. The effective size is determined by the ability of the target to reflect radar signals. Depending on the shape and material of the target, the effective size may vary widely (for example, stealth technology can make a large aircraft appear very small to radar). The measure of effective target size is known as Radar Cross Section (RCS).

Figure 1.9-12 illustrates RADAR cross sections for various target geometries. These figures assume a perfectly reflective (i.e. metallic) target material. The RCS of a vehicle will change based on vehicle size, aspect angle and type of materials used in its construction. Figure 1.9-13 illustrates how RCS can change depending on aspect angles of vehicle targets. With a technology trend towards composite materials and away from metal, the vehicle RCS will most likely decrease. At 77 GHz, the RCS of a vehicle is indicated to be 10 dB, a motorcycle to be 2 dB and a pedestrian to be 0 db.



(Note: r= range to the target, w= target width, h=target height, Lambda= RADAR wave length)

Figure 1.9-12. Examples of Target RADAR Cross Section (RCS) for Based on Target Geometry

(Ref: "Radar Cross Section", microwaves101.com/encyclopedia, 2010 [97])

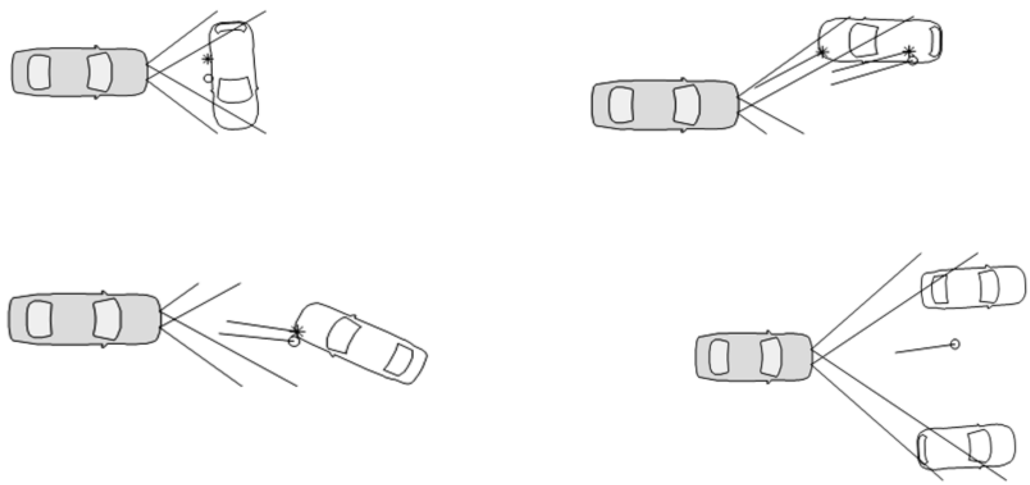


Figure 1.9-13. Examples of Variations in RCS Related to Vehicle Detection
(Ref: "Design of a 24 GHz RADAR with Subspace-Based Digital Beam Forming for ACC Stop-and-Go System"; Seong-Hee Joeng, et al, *ETRI Journal*, Volume 32, Number 5, October 2010 [98])

Challenges of vehicle RADAR sensors were reviewed by Dr. David Schwartz of Delphi in a presentation entitled, "Delphi Sensor Fusion for Automotive Safety" [13], with the following points made:

- "RADARs provide good range and range rate information but are poor at determining the edges (extent) and lateral rates of objects;
- Vision systems are good at classifying objects, determining the edges (extent) and lateral rates, but are very poor at determining range and range rates;
- Sensor fusion between RADAR and vision systems improve target detection and reduce false alarms;
- Accurate Yaw angle and rate are necessary for accurate target positioning; wheel yaw rate sensors do not provide required accuracy;
- RADAR can be replaced with other sensors, but not without effort:

  RADAR has capability of adaptive beam width, gathering multiple returns from a vehicle (using a high PRF), providing accurate ranging, supporting required FOVs, and discriminating fixed form moving targets.

As pointed out above, false alarms and missed detections cannot be tolerated for applications involving safety of life. RADAR, without fusion with other sensors cannot provide the integrity and confidence level required for safety of life applications.

The effectiveness of RADAR also depends on atmospheric conditions as shown in Figure 1.9-14 which illustrates the attenuation of signals as a function of frequency and rain rate. Two typical RADAR bands (24 GHz and 77 GHz) are highlighted in the figure.

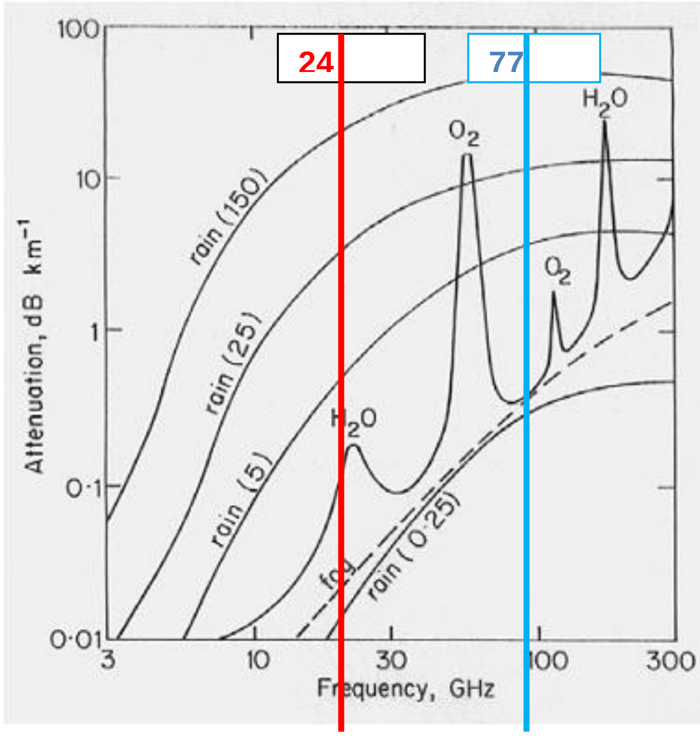


Figure 1.9-14. RF Signal Attenuation as a Function of Frequency and Rain/Fog
(Ref: USDOC, NTIA Document, "Communications Receiver Performance Handbook", JSC-CR-06-072, 2006 [104])

1.9.3 Deployability Assessment

Table 1.9-4 summarizes the pros and cons of a phased array RADAR. Note that through DARPA funding, large scale integration has been accomplished significantly reducing the cost of a phased array RADAR components.

Table 1.9-4. Pros and Cons of a Phased Array RADAR

Advantages	Disadvantages
High Antenna Gain with Low Side Lobes	FOV Limited to 120 Degrees
Adaptable Scan Modes and Patterns	Complex Antenna Structure and Processing Requirements
Ability to Emit Multible Beams Simultaneously	Typically Larger Antenna Area
Loss of One Antenna Element Reduces Beam Shape but does not Cause Total System Failure	

Source: ARINC April 2012

1.9.4 Installation, Test and Calibration

In reviewing one of the installation manuals produced by a major manufacturer of vehicle RADAR for ADAS and ACC, requirements for RADAR sensor alignment with the center line of the vehicle were noted:

- Vertical Alignment: ±1 deg;
- Roll Alignment: ± 0.6 deg;
- AZ Align: ± 2 deg;
- Pitch over ± 2 deg. with a 2 second cycle will cause failure.

Either electrical and/or mechanical alignment provisions are provided. However, any misalignment of the RADAR sensor relative to the vehicle center line will produce a fixed bias error in the azimuth. Thus periodic alignment of the RADAR sensor with car reference will be required. One major RADAR manufacturer states in his installation manual that vertical vibration exceeding ± 2 deg. at a frequency period greater than 2 sec. may cause improper operation

To test the performance and accuracy of an active RADAR sensor, some form of test range will be needed, perhaps using corner reflectors. Alignment and performance checking will be periodically required.

In addition, RADAR is subject to physical maintenance issues. Physical covers, known as radomes, are typically used to protect the sensitive radar antenna. These are designed to minimize impact on the RADAR beam while physically protecting the antenna. Radomes cannot typically be painted or coated with a foreign material; otherwise the antenna pattern will be distorted. This also represents a problem in winter environments where packed snow, salt spray and other materials are likely to affect the performance of the radome.

1.9.5 Applicable Standards

Other than FCC regulations, and roadside equipment environmental and electrical standards equipment, there are no applicable standards governing RADAR systems.

1.9.6 Cost and Life Cycle Status

RADAR technology has been available for decades. For most applications it tends to be a somewhat expensive solution. The dominant improvements that have been made in recent years are through integration of the RADAR transceiver using microwave integrated circuit technology. Today RADAR products for vehicles are considerably less expensive compared with LIDAR and electronically scanned radar has better reliability compared with mechanically scanned LIDAR. New automotive RADAR have embedded target trackers and multiple vehicle RADAR fusion devices are available providing the potential for a 360 deg. “around the vehicle” target detection and ranging capability.

1.9.7 RADAR Technology Evolution and Forecast

RADAR technology is very well established. Most of the technical improvements are in the area of cost reductions. However, as described above a key limitation of RADAR systems is their inability to adequately discriminate between targets of interest and clutter. This is especially problematic in the complex roadway environment. The most promising approach to reduce the effect of this issue is through sensor fusion, where other information (for example, video images or map information) is combined with the RADAR return information to provide a much higher integrity determination of hazards. In these systems the RADAR provides ranging and speed information, but the identification and classification of the targets is done through image analysis or by locating targets in the roadway environment by correlating their position on a digital map. These techniques are described in Section 5.3.

1.9.8 RADAR References

Table 1.9-5. RADAR References

[13] Presentation entitled, “Delphi Sensor Fusion for Automotive Safety” by Dr. David Schwartz of Delphi, *PReVENT/ProFusion2 Fusion Forum Workshop*, March 2006.

1.10 Ultrawideband Transponders

1.10.1 Overview of UWB Technology

An Ultra Wideband (UWB) radio frequency signal is defined as one that occupies more than 500 MHz of spectrum and has a fractional bandwidth (the bandwidth of the signal divided by the center frequency of the signal of more than 0.2.

The most common technique for generating a UWB signal is to transmit pulses with very short durations (less than 1 nanosecond). The spectrum of a very narrow-width pulse has a very large frequency spectrum approaching that of white noise as the pulse becomes narrower and narrower. The frequency spectrum for conventional and ultra wideband RADAR systems is illustrated in Figure 1.10-1 below. As can be appreciated from the figure, the UWB signal is effectively below the noise floor in the frequency domain. In the time domain, however, it is possible to discriminate the pulses, and provide useful and accurate range measurement as well as precisely timed data communications.

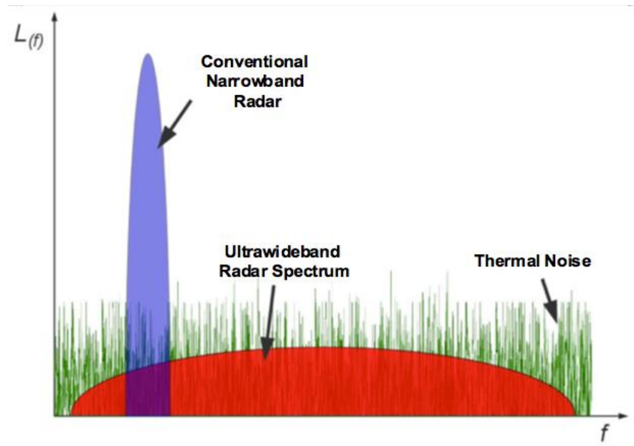


Figure 1.10-1 Ultrawideband RADAR Spectrum
(Ref: Radartutorial.eu, 2011 [107])

One potential issue with UWB is that, because each transceiver is effectively generating white noise, a large number of such transmitters will effectively raise the noise floor. Since the bandwidths are typically quite large, this may have a collateral impact on other communications systems in the affected bands. For this reason, the regulatory situation with UWB is uncertain, especially if they are widely deployed. In addition, UWB devices generally operate under Part 15 of the FCC regulations. This means that they must accept interference from any and all other devices using the band. While the wideband nature of UWB insulates it to some degree from direct narrowband interference (since the modulations schemes are so different), a high level narrowband interferer may saturate the front end of the UWB receiver, and this may disrupt communications.

Ultra Wideband (UWB) radio frequency (RF) ranging was identified in the Task 3 report as having characteristics worth further investigation. There are several potential approaches to UWB ranging, which provides a very accurate range. These approaches include:

- Two way time of flight (UWB RADAR);
- Two way time of flight (transponder);
- Time Difference of Arrival (TDOA);
- Direction of Arrival (DOA);
- TDOA augmented with Direction of Arrival;
- GPS Augmentation (using UWB derived pseudo range).

RADAR positioning was discussed in Section 4.3. Using UWB technology in the RADAR mode provides highly accurate range measurement, but UWB is inherently a low power system, and this limits the range of these applications.

For positioning applications, it is also possible to use UWB in a communications mode. In this approach, the vehicle transmits a message as an encoded pulse string (for example, a pseudo-random code using pulse position or pulse polarity modulation). The message encoding binds the message to the vehicle. This message is then received by transponders located at various fixed points in the roadway environment. The transponders receive and then retransmit the encoded messages. Because this is a re-transmission as opposed to a reflection the signal loss falls off as $1/r^2$ instead of $1/r^4$ as is the case with RADAR. This substantially increases the useable range of the system over the RADAR ranging approach, and this facilitates the use of UWB. The short duration pulses used in UWB also facilitate accurate time of flight determination. As long as any delay at the transponder is known and stable, the range between the vehicle and the transponder can be determined. With pulse widths on the order of one nanosecond, and using the pulse position encoding, the vehicle can determine the range to the transponder to within less than one foot (0.3 meter).

If the locations of at least three transponders are known, and the vehicle has determined the range to each of these transponders, it can then easily determine its own position. Determining the locations of the transponders can be accomplished in various ways. One simple approach is to use DSRC to transmit the transponder locations. Another is to use the UWB system itself to broadcast the transponder locations and IDs. Both of these approaches, however, result in ambiguity about which transponder is associated with which range measurement. These ambiguities can often be resolved by validity checks on the basic position of the vehicle (assuming it has an accurate map, it can use map matching and other techniques to validate that the position determined by the UWB system is consistent with its operation, direction of travel, etc. It is also usually possible to infer the relationships between measured ranges and transponder locations, since confusing the ranges and transponder locations will result in non-consistent solutions (i.e. solutions that do not result in a solvable triangulation problem).

This system is illustrated conceptually in Figure 1.10-2 below. In this figure we have included elements to implement each of the various schemes described above (e.g., DSRC, and/or a UWB access coordination function). We have also included GPS satellites and their pseudoranges to indicate that the transponder ranges TR_n can be combined with GPS pseudoranges to arrive at a hybrid positioning solution. This approach is helpful in situations where GPS coverage is poor.

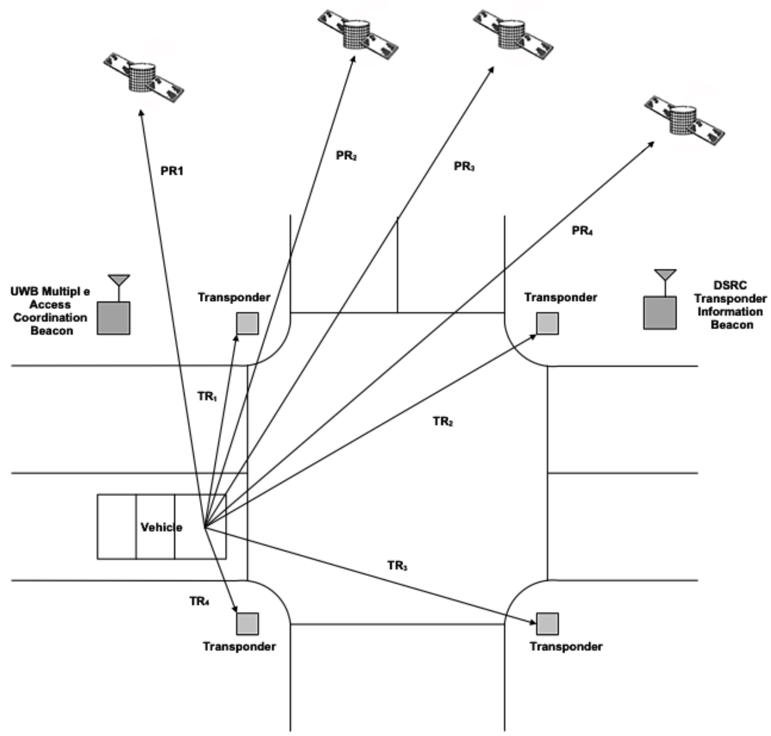


Figure 1.10-2. Illustration of Using UWB Transponders and Beacon at Signalized Intersection to Provide GPS Pseudo Range Augmentation
Source: ARINC April 2012

Another concept is to install both interrogators and transponders in vehicles to allow each vehicle to obtain range from other vehicles. The issues with this approach, which has been tested at the University of Calgary, is that position relative to other vehicles could not be determined without determining both range and bearing. Also, range processing time would limit the number of vehicles that could be accommodated. Another possible approach is to install interrogators as part of the RSE and transponders within vehicle. The range between geo-referenced RSE and the vehicle would then be communicated to the vehicle, either as part of the UWB protocol or via the DSRC. The issues with this approach are that latency would impact accuracy of the range and there is a limit on the number of vehicles that could be serviced (as previously discussed). By adding direction of arrival capability to the roadside UWB ranging interrogator, both range and bearing could be obtained and vehicles tracked by the RSE. The issues with this approach are the vehicle limitations and that there is no clear advantage for RADAR or LIDAR, which do not require transponders in vehicles. However, using UWB ranging transponders would possibly support detection of vehicles masked by larger vehicles, which is a problem for RADAR and LIDAR.

According to the manufacturer of the UWB ranging device, the unit can detect when a direct path is not available and captures the shortest multipath and ranges on it. The interrogator knows that the, measurement is not a direct path; this approach typically has a range accuracy of 50 cm to 1 meter, according to the manufacturer.

Using UWB in communications mode with a large number of vehicles may result in channel capacity issues. Figure 1.10-3 illustrates the relationship between range and channel capacity (channel bandwidth) for UWB systems. As can be appreciated in the figure, as the range increases the available bandwidth decreases. As the range increases the number of vehicles using the channel will also increase, so it is important to balance these competing demands.

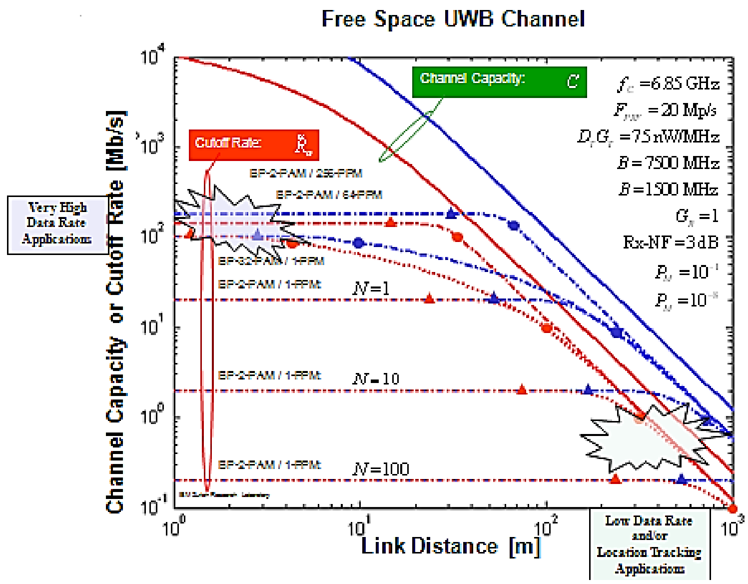


Figure 1.10-3. Theoretical Capability & Application Spaces UWB
(Ref: “UWB: Technology and Implications for Sensor Networks”, Robert Szewczyk, NEST Meeting, August 27, 2004 [57])

1.10.2 UWB RADAR Performance Assessment

UWB transponder based ranging technology is summarized in Table 1.10-1 below.

Table 1.10-1. UWB Transponder Ranging Performance Summary

Minimum Range	354 m with Ranging Time of 103 msec.
Medium Range	177 m with Ranging Time of 26 msec.
Short Range	88 m with Ranging Time of 6 msec.
Range Accuracy	20 cm (1 sigma) @ 200 meters (Does not consider vehicle speed and motion within defined range processing time)
GPS/UWB Kinematic Position	10 cm/95%

Source: ARINC April 2012

UWB allows very accurate measurement of range, and this is expected to result in accurate position determination as long as the positions of the transponders are accurately known.

Figure 1.10-4 presents range resolution versus bandwidth for UWB applications. A 500 MHz bandwidth UWB has approximately a 0.15 meter range resolution. This is achieved by its narrow, nanosecond pulse width.

The doctoral thesis by Glen MacGougan entitled, “Real Time Kinematic Surveying using Tightly Coupled GPS and UWB Ranging” (Ref: [14]) presented test results of UWB providing range errors of 0.35 to 0.50 cm at 100 meters range from UWB transponders. These range errors included bias and scaling errors which can be removed. HDOP of GPS alone (which ranged from 20 to 80) was improved to 1 utilizing GPS-UWB ranging augmentation.

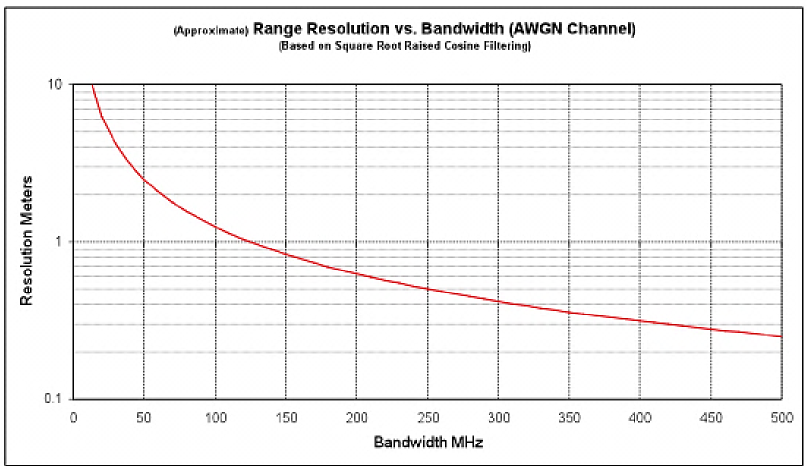


Figure 1.10-4. Range Resolution vs. Bandwidth Using UWB
(Ref: “UWB: Technology and Implications for Sensor Networks”, Robert Szewczyk, NEST Meeting, August 27, 2004 [57])

In a similar University of Calgary thesis (UCGE 20277) by David Chiu, entitled, “Ultra Wideband Augmentation of GPS” (Ref: [58]), a differential GPS receiver was utilized and results compared based on number so satellites visible by the GPS receiver and the number of UWB ranging transponders utilized. Two different UWB radios were utilized. Maximum range was 140 meters. These results are presented in Table 1.10-2 below. This table provides the position errors in terms of meters of error in the east-west direction (known as “easting”) and in the north-south direction (known as “northing”). The table also includes the standard deviations of the measurements (“Std”).

Table 1.10-2. Results of Testing of UWB Augmentation of GPS
(Ref: "Ultra Wideband Augmented GPS", by David Chiu, University of Calgary UCGE Report 20277, December 2008 [58])

GPS Satellite Visibility and UWB Transponders	East (m) + Std	N (m) + Std
7 + 0	-0.112 +- 0.024	-0.062 +-0.030
4 + 3	0.1046 +- 0.107	0.005 +- 0.039
4 + 0	-0.097 +- 0.081	-0.229 +- 0.134
2 + 3	-0.002 +- 0.479	-0.088 +-0.580

Another research report by Glenn MacGougan, et al, entitled, "UWB Ranging Precision and Accuracy" (Measurement Sciences and Technology, Volume 20, Number 9, 2009 [100]), discusses the UWB-GPS integration research at the University of Calgary. This research paper emphasized that sub-meter ranging is possible with UWB, including bias and scaling errors. The ranging errors are first order linear according to the research paper and should be removable. The UWB ranging testing proved resilient to multipath.

Research conducted by Xsens Technologies B.V. in the Netherlands related to UWB-GPs integration is documented in a research paper by Arun Vydhyanathan, et al, entitled, "Augmenting Low-cost GPS/INS with UWB Transceiver for Multi-platform Relative Navigation" [59]. Results are summarized in Table 1.10-3. The report concluded that position accuracies of 0.5 meters (horizontally) with horizontal velocity accuracies of 0.28 m/sec. were possible using UWB augmentation of a low cost GPS/INS. While Pitch and roll accuracies obtained were sub-degree, yaw accuracy obtained (6.25 deg.) does not support navigation supporting safety of life applications. Three UWB nodes were utilized in the test. The conclusion was that increasing the number of UWB nodes will increase performance accuracies. A similar test was conducted by the University of Calgary as documented in a technical paper by Dr. Kyle O'Keefe, et al. entitled, "Demonstration of Inter-vehicle UWB Ranging to Augment DGPS for Improved Relative Positioning: [60]. The paper indicates UWB range errors at approximately 85 meters was 0.5 meters. GPS pseudo range accuracy was stated to be 5 meters and IMU bearing accuracy of 0.5 degrees. Table 1.10-4 presents the results on one test in a residential area comparing differences in navigation configurations. The paper concluded that UWB ranging proved to be most beneficial in "along track" direction and bearing data most beneficial in the cross track direction.

Table 1.10-3. Results of GPS/INS/UWB Integration
(Ref: "Augmenting Low-cost GPS/INS with UWB Transceiver for Multi-platform Relative Navigation", Arun Vydhyanathan, et al, *ION GNSS 2009*, September 2009 [59])

Navigation System Configuration	Position Errors RMS (m)	Velocity Errors RMS (m/s)	Orientation Errors RMS (deg.)
GPS/INS	North: 0.92 West: 0.92	North: 0.36 West: 0.36	Roll: 0.28 Pitch: 0.32 Yaw: 6.49
GPS/INS/UWB	North: 0.52 West: 0.52	North: 0.28 West: 0.27	Roll: 0.29 Pitch: 0.28 Yaw: 6.25

In a University of Calgary doctoral thesis (UCGE 20293, dated August 2009) by Glenn MacGougan entitled, "Real-time Kinematic Surveying using Tightly Coupled GPS and UWB Ranging" [14], concluded (based on field testing) that with 4 to 5 satellites available and with UWB ranging, 1 to 3 cm (1 sigma) position accuracy could be obtained and that sub-meter accuracy could be achieved in urban canyons with less than 4 satellites available.

Table 1.10-4. Results of GPS/UWB Integration Performance Evaluation Test Conducted by University of Calgary
(Ref: "Demonstration of Inter-vehicle UWB Ranging to Augment DGPS for Improved Relative Positioning," Dr. Kyle O'Keefe, et al, University of Calgary, September 2010 [60])

Navigation Configuration	Along Track (m)		Across Track (m)	
	Means	Std Dev.	Means	Std Dev.
GPS ONLY	-9.43	9.69	-1.79	15.37
GPS + UWB	-4.19	6.98	0.63	5.20
GPS + Bearing	9.56	9.28	0.47	11.66
GPS + UWB + Bearing	-4.13	7.10	1.04	5.04

While UWB ranging is generally very accurate, the system is not seen to be particularly practical. Notwithstanding the need for substantial roadside equipment, the problem of coordinating ranges and transponder positions is very complex.

Communications with a manufacturer of UWB products and whose products have been utilized for UWB ranging test at the University of Calgary advertise an operational range of 0.1 m to 354m. The manufacturer uses two way time of flight ranging to increase operational range. Thus range is a function of both time of flight and processing time. Figure 1.10-5 illustrates the time required to measure the range (the range measurement duration) as a function of the range. A range of 88 meters requires 6 msec; 125 meters requires 13 msec; 177 meters requires 26 msec; 250 meters requires 51 msec and 354 meters requires 103 msec. The product is specified as having a 7 mm range resolution and the manufacturer states that range accuracy is 6 cm at 177 meters range.

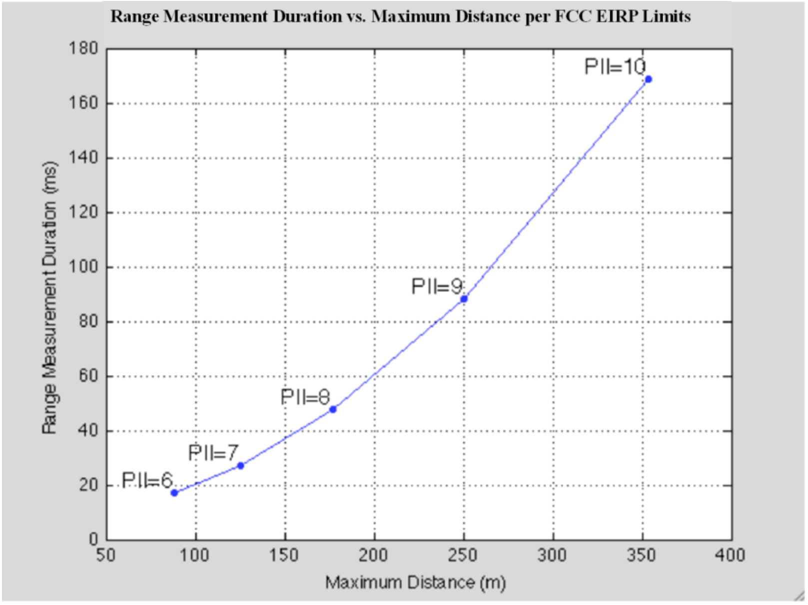


Figure 1.10-5. Example of Range Measurement Time versus Distance for Pulse Integration Index Options

(Ref: O'Keefe, K., et al, "Demonstration of Inter-vehicle UWB Ranging to Augment DGPS for Improved Relative Positioning", ION GNSS 2010, September 2010 [60])

At one range per second per vehicle (the equivalent basic GPS position rate), then each transponder can only serve about 20 vehicles. If ranges are required at a higher rate, then fewer vehicles could be serviced.

This processing time limitation is also problematic for positioning accuracy. A vehicle traveling at 90 km/hr moves approximately 1.27 meters during the ranging process. The manufacturer states that range is averaged during processing and thus the range provided is the mean range between that at the start of the 51 msec interrogation cycle and the location at the end of the 51 msec cycle, and that the error of the mean range is 10 cm. The manufacturer did not have test information for high vehicle velocity and acceleration/deceleration, but they did note that these dynamics impaired range accuracy.

Table 1.10-5 presents range accuracy as a function of speed and processing time. This indicates that 50 cm or less range accuracy is potentially possible at 177 meters range or closer and 20 mph vehicle speeds or at 125 m or less range and speeds to 65 mph.

Table 1.10-5. Vehicle Range Error from an RSE Responder Considering Speed

Vehicle Approach Velocity	Positioning Error with 88 m Range and 6 msec Processing	Positioning Error with 125 m Range and 13 msec Processing	Positioning Error with 177 m Range and 26 msec Processing	Positioning Error with 250 m Range and 51 msec Processing	Positioning Error with 354 m Range and 103 msec Processing
20 mph	12.7 cm	15.8 cm	21.6 cm	32.8 cm	56.0.0 cm
35 mph	14.7 cm	20.2 cm	30.3 cm	49.9 cm	91.0 cm
45 mph	16.0 cm	23.1 cm	36.2 cm	61.3 cm	1.14 m
55 mph	17.4 cm	23.1 cm	36.2 cm	61.3 cm	1.34 m
65 mph	19.0 cm	28.9 cm	47.8 cm	84.2 cm	1.60 m
75 mph	20.0 cm	30.1 cm	53.5 cm	95.5 cm	1.83 m
90 mph	22.1 cm	36.1 cm	62.3 cm	1.13 cm	2.17 m

Source: ARINC April 2012

1.10.3 Deployability Assessment

Table 1.10-6 summarizes the analysis of UWB ranging technology.

Table 1.10-6. UWB Ranging Technology Pros and Cons

Pros	Cons
• Can Provide Kinematic Accuracies; • Small and physically compatible with a car installation; • Good immunity to multipath and narrow band interference; • Can operate in tunnels; • Can operate with small impact on accuracy, with RF path obstruction; • Can provide sub-meter positioning accuracy at short distances from intersection stop lines for vehicles approaching the intersection; • Improves HDOP for GPS Receiver; • Can detect when a direct path is not available and determines range based on shortest multipath.	• Requires Interrogators in vehicles adding additional cost and increasing possible interference with other RF devices associated with the OBE; • Requires Responders and Beacon (manages multiple access) at or near intersections adding to RSE cost, RF emissions, and additional maintenance by jurisdictional signal technicians; • Does not contribute to positioning accuracy except where UWB responders are deployed and is thus not a universal solution. Operates in bands used by GPS, Wi-Fi, and WiMAX that may be utilized for ITS applications. Some manufacturers also have UWB operating in the DSRC frequency band (see FCC Mask for UWB Emissions). Risk of raising the noise floor and impacting data rate of some protocols; • Only works where ranging Responders are deployed and Responders have range limitations; • Range processing time limits the number of vehicles that can be serviced with a reasonable range update rate; • Possible issues with range errors caused by high acceleration/deceleration - -requires testing; • May be limited on Responder Deployment Geometry to Support adequate HDOP; • Cost currently expensive for private vehicles (Around $3000 with antenna and mounting provisions).

Source: ARINC April 2012

1.10.4 Installation, Test and Calibration

Figure 1.10-6 illustrates the current antenna available to support ranging.

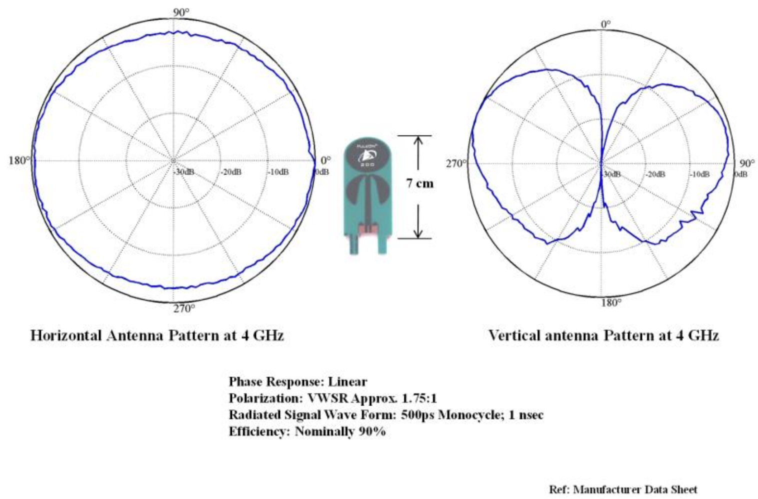


Figure 1.10-6. UWB Antenna Utilized for Ranging
(Ref: Broadspec UWB Antenna, Time Domain Corp. Technical Data, 2010 [106])

1.10.5 Applicable Standards

FCC Document 02-48 entitled, "Revision of Part 15 of Commissions' Rules Ultra Wideband" (4-22-02) [101], defines the operation restriction on UWB. Source: ARINC April 2012

Table 1.10-7 provides an overview of the FCC regulations on UWB EIRP transmissions limits from 0.96 to 29 GHz). The limits on EIRP plus the path loss at higher frequencies contributes to the reasonably short range achieved by UWB devices. The University of Calgary (Ref: [60]) has experienced reliable communications up to 150 meters using UWB.

An example commercially available UWB ranging product operates in accordance with the FCC mask for UWB as shown in Figure 1.10-7, and has an operating center frequency of 4.3 GHz and a bandwidth of 3.1 to 5.3 GHz. This product is specified to operate over a temperature range of -20 deg to +55 deg. C. It does not comply in its current form to NEMA TS-2 environment requirements; however, the manufacturer states that the product can be modified to comply with vehicle and roadside environment requirements. The UWB ranging product is 76 mm x 102 mm x 20 mm requires packaging; power requirements are stated as 6 to 24 VDC at 4 Watts

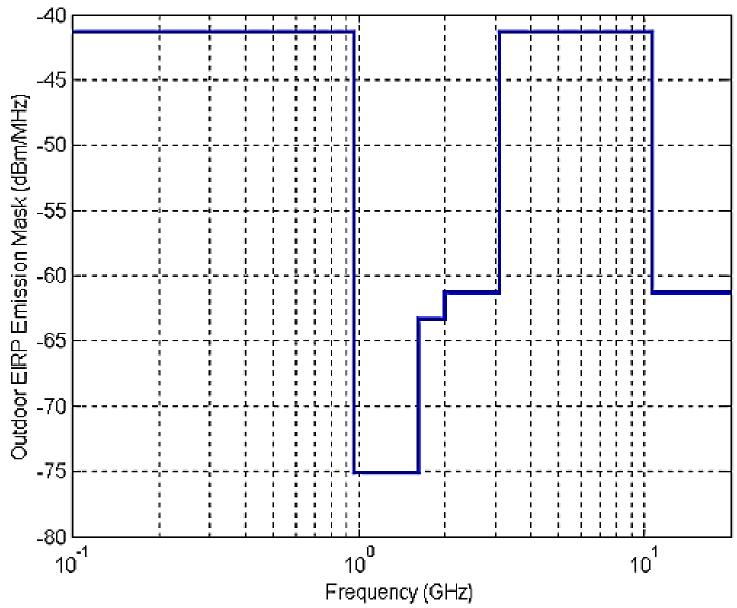


Figure 1.10-7. FCC Mask for UWB Emissions
Source: ARINC April 2012

Table 1.10-7. FCC Regulations on EIRP of UWB Signal Transmissions

Application		Operating Band (GHz) 0.96 to 1.61	1.61 to 1.99	1.99 to 3.1	3.1 to 10.6	10.6 to 22.0	22.0 to 29.0
Communications	Indoor	-75.3	-53.3	-51.3	-41.3	-51.3	-51.3
	Outdoor	-75.3	-63.3	-61.3	-41.3	-61.3	-61.3
Imaging		-53.3	-51.3	-41.3	-41.3	-41.3	-51.3
Vehicular RADAR		-75.3	-63.3	-63.3	-63.3	-41.3	-41.3

Source: ARINC April 2012

There has been much concern over the interference of narrow band signals and UWB signals that share the same spectrum; traditionally the only radio technology that operated using pulses was spark-gap transmitters, which were banned due to excessive interference. However, UWB is much lower power. The subject was extensively covered in the proceedings that led to the adoption of the FCC rules in the US, and also in the meetings relating to UWB of the ITU-R that led to the ITU-R Report and Recommendations on UWB technology. In particular, many common pieces of equipment emit impulsive noise (notably hair dryers) and the argument was successfully made that the noise floor would not be raised excessively by wider deployment of wideband transmitters of low power. However, there remains substantial skepticism that these devices, deployed in large numbers, will not result in widespread interference with existing systems.

1.10.6 Cost and Life Cycle Status

These systems are currently quite expensive. In-vehicle equipment costs about $3000/unit. The system also requires infrastructure transponders wherever the positioning capability was needed. The cost of the infrastructure for a large deployment would be extremely high.

Further development of this technology is clearly required before it can be considered deployable. Example development activities include:

- Conduct field test to verify positioning accuracy and identify any RFI/EMC problems with vehicle having a full complement of ITS related emitters and GPS receiver;
- Modify Product Design to Accommodate the Environment (per SAE and NEMA) and vehicle mounting.
- Develop large scale integrated circuits to reduce production product cost;
- Design interface compatible with OBE firewall router/switch and navigation subsystem;
- Design power supply to operate per SAE and NEMA TS-2 source power specifications;
- Add multiple access protocol capability;
- Develop antenna suitable for vehicles.

1.10.7 Technology Evolution and Forecast

UWB technology continues to advance, although the primary applications appear to be for short-range RADAR imaging. While the technology does not appear to be a viable positioning alternative today, positioning applications are the focus of substantial university research, and it is possible that breakthroughs in system design and implementation could make the concept viable.

1.10.8 UWB References

Table 1.10-8. UWB References

[14] MacGougan, G., "Real-time Kinematic Surveying using Tightly Coupled GPS and UWB Ranging", UCGE 20293, August 2009, University of Calgary, Schulich School of Engineering, August 2009.
[101] Federal Communications Commission, FCC Document 02-48 entitled, "Revision of Part 15 of Commissions' Rules Regarding Ultra Wideband", April 22, 2002.

1.11 LIDAR Systems

1.11.1 Overview of LIDAR Technology

Light Detection and Ranging (LIDAR) sensors operate similarly to RADAR, except that the wave-lengths utilized are in the near IR spectrum. Typically the laser transmitter operates around 904 nm and is safe to eyes. There are several advantages to LIDAR including the ability of receiving returns from non-metallic targets and having a narrow beam width. Also, LIDAR often uses narrow pulse widths that provide superior range resolution to RADAR (except for UWB RADAR).

The laser beam may be continuous wave or pulsed. Pulsed systems provide a “time of flight” measurement similar to RADAR where the travel time of the pulse to the target and back to the LIDAR receiver divided by two, provides the distance measurement. Time-of-flight LIDAR measures time to about 70 picoseconds, which provides centimeter level range accuracy. CW LIDAR provides Doppler detection for measuring target speed.

The standard means for providing horizontal coverage and to maintain high resolution azimuth measurements is to mechanically sweep the laser beam. The laser beam can be swept using a rotating mirror or can use micro-mirrors that are electronically controlled.   These mirrors are manufactured using Micro-Electro-Mechanical Systems (MEMS) technology that basically creates micro scale mechanical structures using variants of semiconductor mask and batch processing techniques. There are other approaches, such as using multiple lasers and an array of laser energy receivers to provide a non-mechanical movement of the laser beams. Like RADAR, a target object needs to have a dielectric discontinuity in order to reflect the laser energy. RADAR produces a reasonable echo for a metallic object; however, some non-metallic objects provide little or no RADAR return. LIDAR provides reflected energy on many soft objects; however, the color of the target may impact its effective detectability since darker objects absorb the laser light, thus resulting in a lower level signal return. LIDAR range is typically shorter than RADAR; therefore LIDAR on vehicles tends to be used for medium range detection applications.

LIDAR is available for both infrastructure based and roadside sensors as shown in Figure 1.11-1.

Figure 1.11-1. Examples of LIDAR for Vehicle and Infrastructure Applications
(Ref: "Reliable Application Specific Detection of Road Users with Vehicle On-board Sensors", ADOSE Report FD7-ICT-2007-1, by E. Schoitsch [61])

LIDAR is commonly utilized for speed enforcement. The laser beam is not scanned in this application and uses pulsed laser and "time of flight" measurement for range. Speed is determined by calculating change in distance versus time between measurements (i.e., range rate); this rate is typically 3 to 4 updates per second. Typical LIDAR speed sensors operate at ranges up to 1000 meters and typically measure vehicle speed form 8 to 320 km/hr (5 to 199 mph) with an accuracy of +- 2 km/hr (1.2 mph). Range resolution is typically 0.1 meters (0.33 ft.), with accuracy of 0.15 meters (0.5 ft.). Most sensors are specified based on a minimum target reflectivity of 10%.

While LIDAR has reasonably good azimuth resolution, vertical resolution is based on the number of sensor layers in the vertical axis. The typical LIDAR has 4 layers of 0.8 degrees, providing elevation coverage of 3.2 deg. While it is possible to have both vertical and horizontal sweep, this makes the sensor more expensive. Figure 1.11-2 illustrates a Flash LIDAR that has been developed for U.S. Department of Defense applications. The Flash LIDAR illuminates the target area with a dispersed flash of energy and then uses an array of sensors to detect the reflected pulse energy. This creates a 3D image with a range accuracy of about10 cm and an azimuth accuracy of around 0.35 degrees. The sensor array can be expanded or improve angular accuracy. The Flash LIDAR has no moving parts and is small (1331 cm^3/ 0.047 cu. ft.). It has the advantage over a scanned laser of having a fixed receiving array, which makes it easier to stabilize.

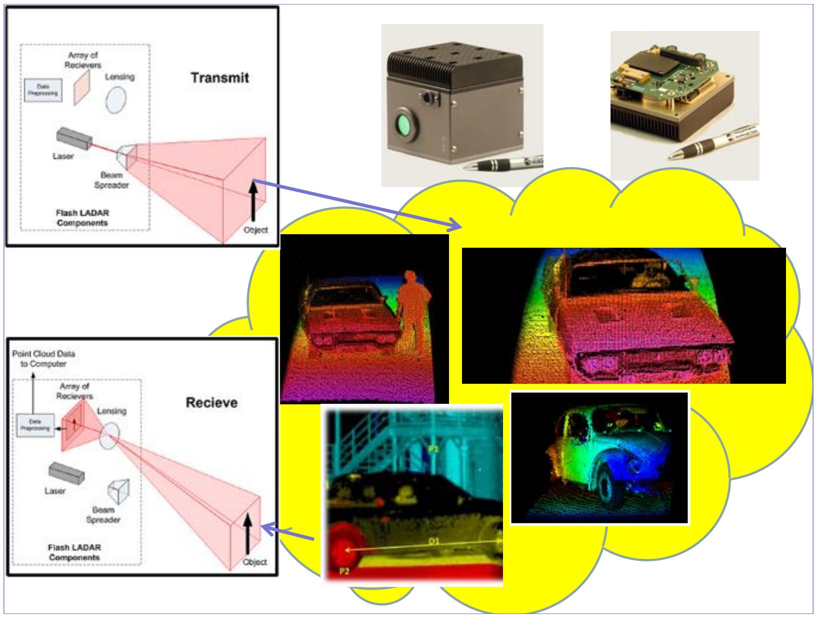


Figure 1.11-2. Flash LIDAR; Small with No Moving Parts
(Ref. Advanced Scientific Concepts Technical Product Literature, 2010 [62])

1.1.1.3 Vehicle Based LIDAR

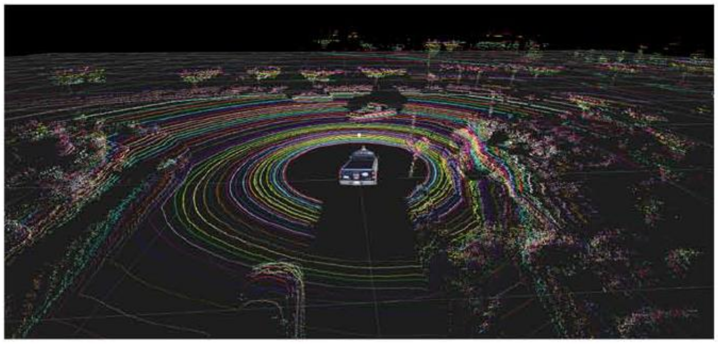
LIDAR has been used extensively in vehicle applications beginning with experimental adaptive cruise control systems in the early 1990’s. Many high-end vehicles today use production LIDAR systems for this purpose today. These relatively low cost systems generally provide simple ranging to the vehicle in the lane ahead, and do not typically provide substantial field of view.

For higher definition, wide field of view applications such as automated driving, scanning systems are available. These are generally production level products that are used in experimental vehicles. Examples include the units from Velodyne shown in Figure 1.11-3. The physical configuration of one of the units is illustrated in Figure 1.11-4.

Figure 1.11-3. Velodyne HDL-64E (Left) and HDL-32E (Right) Scanning Vehicle LIDAR Units
(Ref: Velodyne Inc., Technical Product Literature, 2010 [63])

Figure 1.11-4. Velodyne HDL-64 LIDAR Physical Arrangement
(Ref: Velodyne Inc., Technical Product Literature, 2010 [63])

These systems are able to produce a very high resolution “range image” that can be used to identify and track a variety of objects of interest, including other vehicles. An example of this image is shown in Figure 1.11-5.



Actual point cloud image from HDL-64E S2 showing vehicle at intersection and other vehicles in vicinity along with road features.

Figure 1.11-5. Range Image Produced by Velodyne HDL-64 LIDAR Unit
(Ref: Velodyne Inc., Technical Product Literature, 2010 [63])

Vehicle based LIDAR units have also been employed to detect lane lines and road edges. In a paper published by Denso [64], the system shown in Figure 1.11-6 was described. This system used LIDAR to sense road reflectors and the lane markings, and then used this information to provide lane guidance for the vehicle. This system is illustrated in operation in Figure 1.11-7.

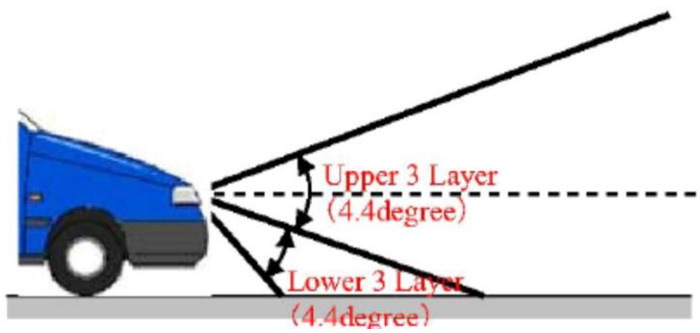


Figure 1.11-6. Lane Detecting LIDAR
(Ref: “Lane Recognition Using On-vehicle LIDAR”, Takashi Ogawa & Kiyokazu Takagi, Denso, Corp., *Proceedings of the Intelligent Vehicles Symposium 2006*, June 13-15, 2006, Tokyo, Japan [64])

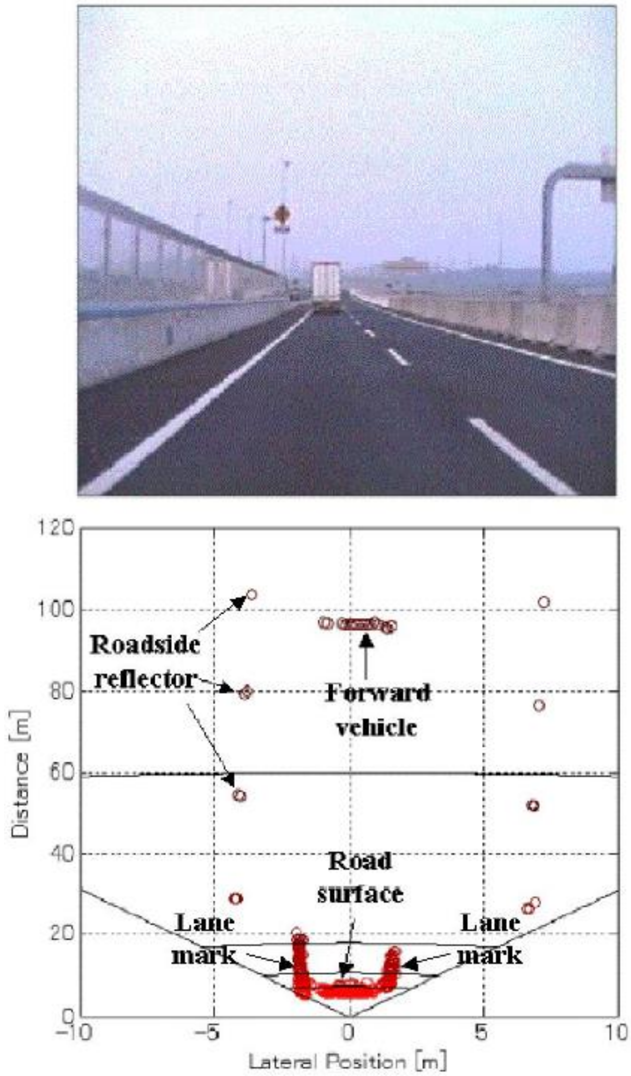


Figure 1.11-7. Forward Image and Resulting LIDAR Detections for Denso Lane Detection LIDAR System

(Ref: "Lane Recognition Using On-vehicle LIDAR", Takashi Ogawa & Kiyokazu Takagi, Denso, Corp. *Proceedings of the Intelligent Vehicles Symposium 2006*, June 13-15, 2006, Tokyo, Japan [64])

1.11.1.1 Infrastructure Based LIDAR

LIDAR has also been used extensively for infrastructure related traffic detection sensors. There are various versions of Infrastructure LIDAR sensors including multiple fixed beams and scanning beams. A dual scanning beam configuration is shown in Figure 1.11-8. Figure 1.11-9 illustrates other deployment configurations. The over road/down looking installation geometry is the preferred configuration by manufacturers.

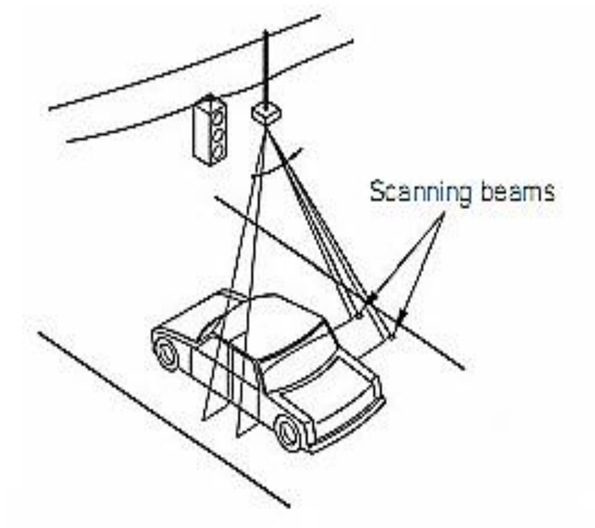


Figure 1.11-8. Example of Over the Road LIDAR Operations
(Ref*:* Federal Highway Administration, "Traffic Detector Handbook", FHWA-HRT-06-108, October 2006 [65])

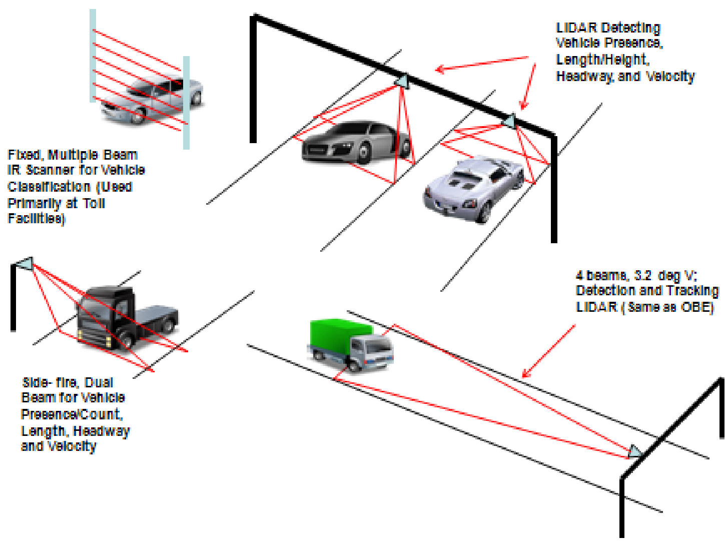


Figure 1.11-9. Example of LIDAR Deployment Configurations for Infrastructure Applications
(Ref*:* Federal Highway Administration, "Traffic Detector Handbook", FHWA-HRT-06-108, October 2006 [65])

A University of California Davis under a Caltrans project developed a prototype Laser Scanner that is shown in Figure 1.11-10; a diagram illustrating the dual transmitter and receiver configuration is presented in Figure 1.11-11 . This sensor is mounted 2 m (6.4

ft.) above the corridor and uses two lasers operating at a wavelength of 905 nm. The two lasers have beam widths of 10 to 60 degrees (fan) and are adjusted to cover a 5 meter (16.4 ft.) width and 5 m (16.4 f.) length of the corridor. Pulse width is 15 nsec, with a pulse rate of 10 KHz. A 104.6 km/hr (65 mph) vehicle transitions the two laser beams in 17.5 msec. The sensor measurement error is 1.14%. Probability of detection is 99%. Vehicle length measurement error is 1 cm (0.4 in.), based on test results.

Figure 1.11-10. UC Davis-Caltrans Real-Time Laser-Based Prototype Detection System for Measurement of Delineations of Moving Vehicles
Source: ARINC April 2012

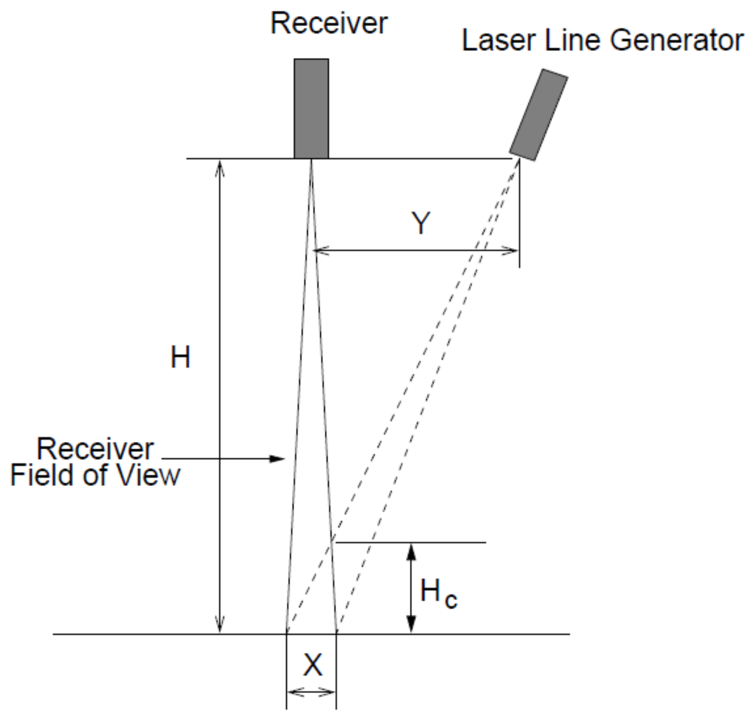


Figure 1.11-11. System Architecture of UC Davis-Caltrans Laser Based Vehicle Detection Sensor
(Ref: "Development and Field Test of a Laser-Based Nonintrusive Detection System for Identification of Vehicles on the Highway"; H. Cheng, et al; *IEEE Transactions on ITS*, Vol. 6, #2; June, 2005 [66])

1.11.2 LIDAR Performance

Scanning LIDAR is utilized in traffic detection and safety applications. The laser beam is typically scanned using a rotating mirror. MEMS devices are emerging that support laser scanning from 500 to 4000 scans per second.

A typical LIDAR utilizing scanning technology is:

- Laser: 905 nm wave length, pulsed, 5 nsec pulse width;
- PRF: 100 to 500 Hz;
- Angular Resolution: 0.5 or 0.25 degrees (selectable);
- Scanning Frequency: 25 to 50 Hz, selectable;
- Horizontal: 90, 120, 160, to 270 degrees;
- Range: 120 meters (394 ft.);
- Range Accuracy: < 2 cm (0.79 in.) (one sigma);
- Systematic error: +- 35mm (0.14 in.).

Some sensors provide a vertical scan covering 26.8 degrees, with a vertical angular resolution of 0.4 degrees using 64 lasers. Angular resolution for this sensor is 0.09 degrees in azimuth. Range accuracy is specified as < 5 cm (2 in.) at 120 m (394 ft.) with a target reflectivity of 80%. Processing latency is specified as < 0.05 msec. LIDAR type roadside sensors are available with environmental specifications compliant with NEMA TS-2 requirements.

Table 1.11-1 presents a summary of LIDAR devices available on the market. The information provided in this table was developed from product data sheets.
Few of the OBE related LIDAR comply with SAE temperature ranges. A number of the products did include a shock and vibration specification of:

- Shock: 100 g, 10 msec, half sine;
- Vibration: 40 m/s^2 peak @ 10 to 60 Hz; 20 m/s^2 peak @ 60 to 200 Hz.

Many of the manufacturers included a maximum range for 10% laser energy remission from a target. The 10% remission range typically is specified as 50 meters (164 ft.). Range accuracy of production LIDAR is around +- 0.1 meter. Target revisit rate varies based on horizontal angle and scan rate, and typically is 20 to 100 msec.

Table 1.11-2 provides the performance characteristics of several infrastructure LIDAR systems available on the market.

Table 1.11-1. LIDAR Products Available on the Market and Performance Information as Provided on Manufacturer's Data Sheets

LIDAR Parameters	Product A, Company A	Product B, Company A	Product C, Company B	Product D, Company C	Product E, Company D	Product F, Company D	Product G, Company E	Product H, Company F	Product I, Company G	Product J, Company H
LIDAR Type	Pulse	Pulse	CW	Pulse	Pulse	Pulse	Pulse	CW	CW	Pulse
Wave Length	895 to 915 nm	895 to 915 nm	904 nm	904 nm	905 nm	905 nm	905 nm	870 nm	905 nm	Flash LIDAR, 1570 nm
Pulse Width	4.5 nsec	4.5 nsec	33 nsec, 45 mW	NA	5 nsec	5 nsec	5 nsec	NA	NA	NA
Horizontal Coverage	85 deg; Extendable to 110 deg.	100 deg.	27 deg.	95 deg. Extendable to 110 deg.	360 deg.	360 deg.	270 deg.	36 deg.	240 deg.	45 deg.
Vertical Coverage	3.2 deg. 4 parallel channels	3.2 deg. 4 parallel channels	12 deg.	3.2 deg.	28.8 deg.	40 deg. 32 lasers	NA	4 deg.	3.2 deg.	22 deg.
Range	0.3 to 200 m (0.98 to 656.2 ft.)	0.3 to 200 m (0.98 to 656.2 ft.)	1 – 10 m (3.3 to 32.8 ft)	0.3 to 50 m (0.98 to 164 ft)	120 m (cars)	0.3 to 100 m (0.98 to 328 ft.)	0.1 to 60 m (0.33 to 197 ft)	0.1 – 130 m (0.98 to 427 ft)	0.3 to 80m (0.98 to 262.5 ft)	150 m (492 ft)
Range with 10% Remission	50 m (164 ft.)	50 m (164 ft.)	NA	Same as Above	50 m (164 ft.)	50 m (164 ft.)	30 m (98.4 ft.)	NA	NA	NA
Range Resolution	0.4 m (1.3 ft)	NA	1 mm (0.04 in)	40 mm (1.6 in)		NA	NA	0.075 m (3 in)	1 cm (0.39 in)	15 cm (5.9 in)
Range Accuracy	0.1 m 1 sigma (0.33 ft)	NA	±0.1 m (3.9 in)	±0.1 m (3.9 in)	2 cm (0.8 in)/(1 sigma)	±5 cm (1.96 in) to 100 m (328 ft)	0.1 to 10 m ±30 mm; 10 to 30 m ±50 mm	±0.5 m (19.7 in)	±5 cm (2 in)	±10 cm (3.9 in)
Horizontal Angular Resolution	0.125 deg.	0.125 deg.	NA	0.125, 0.25, 0.5 deg	0.09 deg.	NA.	0.25 deg.	NA	0.25 deg.	0.35 deg.
Vertical Resolution	0.8 deg; each layer; 4 total	0.8 deg; each layer; 4 total	NA	0.8 deg; each layer; 4 total		NA	NA	NA	0.8 deg; each layer; 4 total	0.2 deg
Horizontal Divergence of Collimated Beam	0.08 deg.	NA	NA	NA	NA	NA	NA	NA	< 0.8 deg.	NA
Echoes per Shot	3	3	3	3	NA	3	3	3	3	NA
Scan Frequency	12.5, 25, 50 Hz	12, 25 Hz.	100 Hz	12.5, 25, 50 Hz	5 to 15 Hz	5 to 20 Hz	40 Hz.	10 Hz	10 to 40 Hz	30 Hz
Velocity	NA	NA	5 – 160 km/hr (3.1 to 99.4 Miles/hr)	NA	NA	NA	NA	0 - 51 m/sec (0 to 167.3 ft/sec)	-250 to + 250 km/hr (-167 to + 167 mph)	NA
Velocity Accuracy	NA	NA	±2 km/hr (1.24 Miles/hr) (±10%)	NA	NA	NA	NA	NA	±1 to ±3.6 km/hr (±0.62 to ±2.2 mph)	NA
Size (H, W, D)	88, 164.5, 92.2 mm (3.5, 6.5, 3.6 in)	80, 120, 80 mm (3.1, 4.7, 3.1 in)	73, 150, 36 mm (2.9, 5.9, 1.4 in)	88, 164.5, 93.2 mm (3.5, 6.5, 3.7 in)	254 mm Tall; 203 mm dia. (10 in Tall; 8 in. dia.)	15 cm (5.9 in) high by 8.6 cm (3.4 in) dia.	80, 103, 80 mm (3.1, 4.1, 3.1 in)	85, 147, 74 mm (3.3, 5.8, 2.9 in)	95, 150, 90 mm (3.7, 5.9, 3.5 in)	11, 11.3, 10.7 cm (4.3, 4.5, 4.2 in)
Weight	1 kg (35.3 oz.)	500 g (17.6 oz.)	160 g (5.64 oz.)	1 kg (35.3 oz.)	13.2 kg (29 lb)	1 kg (35.3 oz.)	700 g (25 oz.)	495 g (17.5 oz.)	1.3 kg (45.8 oz.)	1.6 kg (3.5 lbs)
Power	9-27 VDC, 10 W	9-27 VDC, 10 W	7.5-16 VDC, 1.8W	9-27 VDC, 10 W	15 VDC; 60 W	9 -27 VDC, 10 W	9-27 VDC, 8 W	7.5-16 VDC, 7 W	7.5-16 VDC, 12 W	24 VDC; 30 W
Environmental Temp Operational	-40 to + 85 deg C.	-40 to + 85 deg C	-40 to + 95 deg C.	-40 to + 70 deg. C.	- 10 to + 50 deg. C.	-40 to + 85 deg C.	-40 to + 85 deg C	-30 to + 70 deg C.	-20 to + 70 deg. C.	0 to + 55 deg. C.
Interface	CAN and 100 Mbps Ethernet	CAN and 100 Mbps Ethernet	CAN	CAN and Ethernet	Ethernet	100 Mbps Ethernet	CAN and 100 Mbps Ethernet	CAN	CAN	Ethernet

Source: ARINC April 2012

Table 1.11-2. Specifications from Available Infrastructure LIDAR Products

Infrastructure LIDAR Parameter	Infrastructure LIDAR Product A	Infrastructure LIDAR Product B	Infrastructure LIDAR Product C
Horizontal FOV	35 deg	60 deg.	90 deg.
Angular Resolution	1 deg.	0.67 deg.	1 deg.
Scans per Second per Beam	360	360	120
Beams	2	2	2
Vehicle Detection Accuracy (In Beam Scan)	99%	99%	99%
Vehicle Classification Accuracy (6 Classes)	95%	95%	95%
Length Measurement Accuracy	±10%	±10%	±10%
Vehicle Velocity Measurement Accuracy	±10%	±10%	±10%
Vehicle Height Measurement Accuracy	±76 mm (±3 in)	±76 mm (±3 in)	±25 mm (±1 in)
Interface	EIA 422; Ethernet Option	EIA 422; Ethernet Option	EIA 422; Ethernet Option
Power	90 to 140 VAC, 50-60 Hz, 35 W	90 to 140 VAC, 50-60 Hz, 35 W	24 VDC, 35 W
Size (L,W,H)	455 x 244 x 155 mm (17.9 x 9.6 x 6.1 in)	406 x 343 x 127 mm (16 x 13.5 x 5 in)	279 x 241 x 114 mm (11 x 9.5 x 4.5 in)
Weight	9.3 kg (20.5 lbs)	13.1 kg (29 lbs)	5.4 kg (12 lbs)
Operating Temperature	-40 to + 70 deg. C. (-40 to + 160 deg. F.)	-40 to + 70 deg. C. (-40 to + 160 deg. F.)	-40 to + 70 deg. C. (-40 to + 160 deg. F.)
Wind Load	22 m/sec with gust to 37 m/sec. (43 knots with gust to 73 knots)	22 m/sec with gust to 37 m/sec. (43 knots with gust to 73 knots)	22 m/sec with gust to 37 m/sec. (43 knots with gust to 73 knots)
Rain (operational)	20 mm/hr. (0.8 in/hr)	20 mm/hr. (0.8 in/hr)	20 mm/hr. (0.8 in/hr)
Snow Load	98 kg/m^2 (20 lb/ft^2)	98 kg/m^2 (20 lb/ft^2)	98 kg/m^2 (20 lb/ft^2)

Source: ARINC April 2012

As shown in the table above, the best range accuracy is ±25 mm (±1 in) at distance of around 10 to 15 meters (32.8 to 49.2 ft) with an azimuth angle resolution of 0.67 degrees. Where longer range, rage accuracy and azimuth accuracy is required, OBE LIDAR products should be considered. Over the road LIDAR can be geo-referenced, facilitating the vehicle detection to be “tagged” with location. Since vehicle length can be measured to an accuracy of ±10% and vehicle width can be measured to an accuracy of ±5% (function of aspect to the scanning beam), a vehicle can be positioned to a geo-referenced location to around 50 cm (19.7 in) in the direction of travel and 10 cm (3.9 in) cross track using a laser. At a scan rate of 360 Hz, point revisit latency is 3 milliseconds. One advantage of an over the road LIDAR has is the ability to profile a vehicle and determine boundaries.

1.11.3 Deployability Assessment

In a research report entitled, “Evaluation of Cost Effective Sensor Combinations for a Vehicle Pre-Crash Detection System” (John Carlin, et al, Cal Poly San Luis Obispo, *Proceedings of the 2005 Commercial Vehicle Engineering Congress and Exhibition*, November 2005 [16]), it is reported that LIDAR has an operating range of 150 m, with a range accuracy of +- 0.3 m. This research listed LIDAR as being high in cost, and having a high computation overhead. It listed LIDAR as having some potential object discrimination and listed LIDAR as being capable of detecting a 1" square object. Research of LIDAR cost under this project indicates this technology cost over twice that of vehicle radar; it is expected to come down in cost. FLASH LIDAR is significantly higher because its market has been oriented towards military and NSAS applications.

Like RADAR, the LIDAR must be aligned with the reference system of the vehicle and calibration must be periodically checked. The narrow beam width of the laser makes it more susceptible to vehicle vibration. The laser is also more susceptible to the environment compared with RADAR.

The European PrEVENT project report entitled, "State-of-the-Art of Sensors and Sensor Data Fusion for Automotive Preventive Safety Applications (PR-13400-IPD-040531-v10 [17]), list some pros and cons of LIDAR which include:

Pros	Cons
• Wide, adjustable azimuth angle; • High accuracy azimuth angle measurement; • High range accuracy compared with other sensors (except impulse, UWB RADAR); • Essentially no bandwidth restrictions; • Imaging capability (some configurations).	• Shorter range compared with RADAR; • Missing direct velocity measurements like RADAR (evolving Doppler LIDAR may solve this issue if affordable); • More difficult to install and align in a vehicle compared with RADAR; • Limited vertical resolution; • More difficult to stabilize in a moving vehicle compared with RADAR; • Target "cross section" different from RADAR and influenced not only by aspect angle but roughness, texture and color of material (black vehicle can impact return signal); • Some sensors include mechanical scanning (reliability and environmental concerns); • Generally larger, heavier and require more electrical power compared with RADAR; • Due to detection of small targets (1 sq. in.) increase in false alarms (unless 3D imaging is used); • Latency; • Generally higher cost for vehicle applications.

Source: ARINC April 2012

In its current deployment applications, jurisdictions are primarily concerned about relative location, which is determined during the installation design of the sensor and the intersection of the sensor field of view with the corridor. This provides needed traffic parameters such as presence, count, headway, vehicle classification, and velocity at the selected vehicle detection location. Thus the infrastructure LIDAR can provide corridor and intersection statistics, signal calls, vehicle classification for tolling, oversize warning for large vehicles (approaching narrow bridges and low underpasses), etc. Cost of LIDAR compared with over the road RADAR and video detection sensors has limited its deployment (Ref: "USDOT Highway Financial Data and Information", which lists RADAR and VIDs cost at around $3,500 and LIDAR at $6500-$14,000 [18]). Also like RADAR sensors used for infrastructure sensing applications, vehicle masking by other vehicles is a consideration except for over-lane, down looking installations. Jurisdictional signal technicians are capable of maintaining infrastructure LIDAR at the “black box” interchange, alignment and operational verification service level.

1.11.4 Installation, Test and Calibration

In reviewing one of the installation manuals produced by a major manufacturer of vehicle LIDAR for ADAS and ACC, requirements for LIDAR sensor alignment with the center line of the vehicle were noted:

- Vertical Alignment: ±1 deg;
- Roll Alignment: ±0.6 deg;
- Azimuth Alignment: ± 2 deg;
- Pitch: ±2 deg. with a 2 second cycle will cause failure (this is a result of longitudinal axis of the vehicle tilting up and down under acceleration and braking)

Electrical and/or mechanical alignment provisions are typically provided. However, any misalignment of the sensor relative to the center line of the vehicle will produce a fixed bias error in azimuth. Thus periodic alignment of the sensor will be required.

To test the performance and accuracy of an active LIDAR sensor, some form of test range will be needed, perhaps using corner reflectors. Alignment and performance checking will be periodically required.

1.11.5 Applicable Standards

Table 1.11-3 lists classification of lasers; commercial LIDAR sensors are defined as Class 1 and are thus not harmful to the human eye.

Table 1.11-3. Laser Classes (Ref: American National Standards Institute, “Laser Safety Standards”, ANSI Standard Z136, 2007 [102])

Laser Class	Safety Concern
Class I	Not hazardous for continuous viewing, or access to radiation is prohibited.
Class II	Visible light lasers that can cause damage if viewed directly for extended periods of time.
Class IIa	Visible light lasers not intended for viewing. Eye damage can be caused if viewed directly for more than 1000secs (16.67 min).
Class IIIa	Not hazardous if viewed momentarily. Damaging if viewed through collecting lenses.
Class IIIb	Hazardous to eyes and skin if viewed directly.
Class IV	Hazardous to eyes if viewed in any way. Fire hazard. Could cause skin burn.

Source: ARINC April 2012

1.11.6 Cost and Life Cycle Status

LIDAR systems have been in production for 15 years or more. They are available in a variety of configurations and at a variety of price points. The basic cost metric appears to be the number of laser diodes used and the complexity of the scanning system. For comparative purposes, the single diode laser rangefinder manufactured by SICK (a Russian company), provides 180 degree coverage in a single scanned beam with about 10 mm of range resolution. This unit sells for under $10K. The Velodyne units described above include 64 laser diodes and a much denser and lower latency range image.

These units sell about ten times the price of the single laser. Aside from overall physical complexity, the primary cost driver for these systems appears to be market demand. Currently these higher precision scanning sensors are used for research purposes, and so they are priced and sold as laboratory instruments. The emergence of the SICK sensors at 1/10th the price of the Velodyne system (and used by nearly all of the DARPA Urban challenge researchers) indicates that there may be substantial price elasticity remaining in this technology.

1.11.7 Technology Evolution and Forecast

LIDAR is well developed, and the supporting laser diode technology is mature. Most lifecycle improvements are expected to come from integration of these devices with video systems to improve target identification and tracking, and with improved algorithms to support more sophisticated target identification and tracking.

1.11.8 LIDAR References

Table 1.11-4. LIDAR References

[16] Carlin, J., et al," Evaluation of Cost Effective Sensor Combinations for a Vehicle Pre-Crash Detection System",Cal Poly San Luis Obispo, *Proceedings of the 2005 Commercial Vehicle Engineering Congress and Exhibition*, November 2005.
[17] Strobel, T., "State-of-the-art of Sensors and Sensor Data Fusion for Automotive Preventive Safety Applications", PR-13400-IPD-040531-v10, University of Passau, July 19, 2004.
[18] USDOT Highway Financial Data and Information

1.12 <u>Video Systems</u>

1.12.1 Overview of Video Technology

Cameras for vehicles are available to provide the driver with vision on the sides of vehicles (primarily for large vehicles) and to the rear. Cameras are also utilized for forward vision enhancement and support functions such as lane keeping, pedestrian detection and collision avoidance, traffic sign detection/message extraction, and other functions. IR cameras are utilized for night vision enhancement.

A key challenge in video image processing is that two adjacent pixels in the image may be associated with different objects that have different range. In the 2-dimensional image there is no information to inform the system that these pixels are or are not related. In a roadside video processing environment, the background is not changing and thus the processor can detect objects that are moving from frame to frame by simply comparing the two successive frames. This essentially allows the system to subtract out all of the scene elements that are not moving, and then analyze the differences between the frames to identify moving objects such as vehicles. This technique works well as long as the camera does not move substantially between frames. In situations where there is substantial movement (e.g., in high winds), more processing is required. This is, to a large degree similar to the image stabilization found in many consumer video cameras.

One of the difficulties in video frame processing from a vehicle is that the background scene is continually changing, so this frame comparison technique cannot be used. Thus the detection and safety threat classification algorithm becomes more complex for vehicle video processing. Aside from driving systems cost, this issue increases processing time and resulting latency.

Video systems can use ranging (RADAR or LIDAR) to enhance image processing. An article entitled, "Solid or Not Solid: Vision for RADAR Target Validation", by Amir Sole, et al, [19] describes this process.

Essentially, targets that can be detected based on shape, for example, a car or a pedestrian, are identified in the video image. The radar range "image" (i.e. the range returns as a function of the azimuth or lateral dimension) is then compared to the identified objects in the video image. This effectively allows the system to bind pixels in the image to a given range. Range returns without any corresponding image elements are identified as "ghosts" (generally arising from reflected radar signals) and ignored. Range returns for multiple objects, for example, a smaller object in front of a larger object, can also be differentiated since they have different range returns.

A different way to obtain range information is to use stereo imaging. This approach uses two cameras mounted a fixed distance apart laterally, for example, on the right and left sides of a vehicle. Each camera image is slightly different because of the parallax effect. The difference in position of objects in the two images will be greater for objects close to the camera and lower for objects farther from the camera. This is the same effect that humans use to evaluate the relative distances of objects.

Using this approach, a project sponsored by Toyota and carried out by the Robotics Institute at Carnegie Mellon University, a video system with a one vehicle wide baseline was able to resolve a soda can at 100 meters.

Target detection and recognition is a critical part of video processing. In an article by Fatih Porikli, et al, Mitsubishi Electric Research Labs, TR2007-04, entitled, "Integrated Detection, Tracking and Recognition for IR Video Based Vehicle Classification" [20], tests show that algorithms support only around 90% accuracy in target classification. This is similar to results presented in an article by Cristiano Premebida, entitled, "A LIDAR and Vision Approach for Pedestrian and Vehicle Detection and Tracking" [21], which indicates an 84% success rate. In an article by C. G. Keller, University of Heidelberg, entitled, "Dense Stereo-Based ROI Generation for Pedestrians" [22], analyzing the stereo images over a 12-27 meter (39.4 to 88.6 ft) longitudinal and 8 meter (26.3 ft) lateral area provided a target range error of 30% and a target lateral error of 10%. An article by Uwe Rranke of DaimlerChrysler AG, entitled, "From Door-to-Door: Principles and Applications of Computer Vision in Driver Assisted Systems" [23], suggests 400 msec latency associated image processing (with new quad processor computers, perhaps this latency would be around 200 msec).

Video sensors are available in sizes compatible with vehicle installation. A typical size range is:

- Height: 40 to 60 mm (1.57 to 2.4 in) ;
- Width: 60 to 90 mm (2.4 to 3.54 in);
- Depth: 60 to 75 mm (2.4 to 2.95 in);
- Weight: 0.3 to 0.5 kg (10.6 to 17.6 oz.).

The units available from vehicle manufacturers are designed for compatibility with SAE (or European equivalent) environmental and power standards; however, some of the aftermarket vehicle video sensors have non-compatible environmental specifications (such as -30 degrees C to + 50 degrees C (-22 to 122 deg F) operating). The cameras are available with visual and IR spectrum capability, and exhibit scene illumination sensitivities of around 0.1 Lux. Viewing angle is tailored to the application with side and rear cameras having a wider FOV (around 130 degrees) with forward-looking cameras having around 40 degrees FOV. Cost varies based on quality and features. Low-end aftermarket units for rear and blind spot vision cost around $150. High-end vision systems with target detection and tracking cost around $1000.

Automated image processing with target recognition and tracking are not included in the dimensions and weight above. The video processing unit is a separate unit and may be provided be a separate supplier. The video processing software is considered to be proprietary and performance information was denied by manufacturers.

For a stand-alone, mobile video system with automatic, potential safety threat target detection, tracking and relative position reporting requires considerable processing. In research report entitled, “Multiple Vehicle Detection and Tracking in Hard Real Time” [24], by Margrit Betke, et al (University of Maryland), it is pointed out that 98 msec of processing time is required (on an average) for each frame of video. This is in addition to the frame capture time that is a function of frame rate. There are a number of approaches used for target recognition including pattern matching and behavior analysis; in a research report entitled, “Automatic Target Classifier Using Model Based Image Processing” [25], by Douglas Haanpaa, it was emphasized that a minimum of 5 pixels are required for target identification. Thus the mobile camera pixel rarity size (the number of pixels that represent any given object in the scene) is important not only to target recognition but also the accuracy of extracting target range and bearing.

Figure 1.12-1 illustrates one of a number of available video processing system approaches.

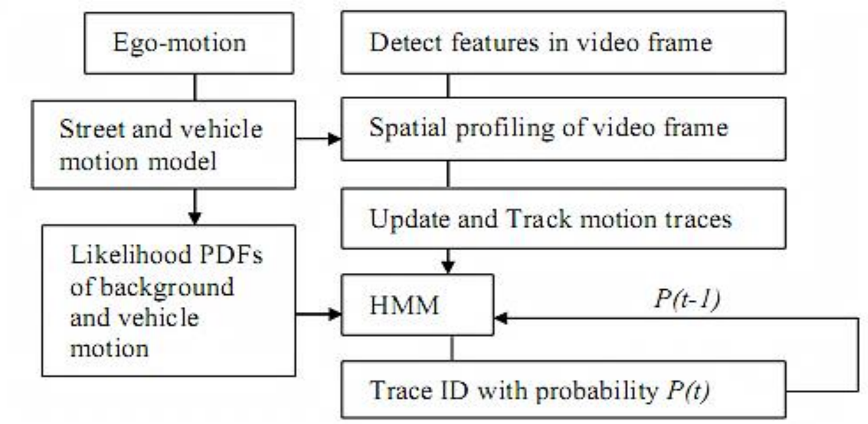


Figure 1.12-1. Example of Video Processing Associated with Potential Threat Recognition and Tracking and Using a Hidden Markov Model Approach
(Ref: "Vehicle Detection and Tracking in Car Video Based on Motion Model", A. Jazayeri, et al, Purdue University, *IEEE Transactions on Intelligent Transportation Systems*, Volume 12, Issue 2, 2011 [67])

As with all in-vehicle sensors, they must be aligned with the vehicle reference system. The video image must be calibrated, establishing the appropriate location of the vanishing point with pixel (x,y) referencing. Figure 1.12-2 illustrates a road vanishing point and camera geometry.

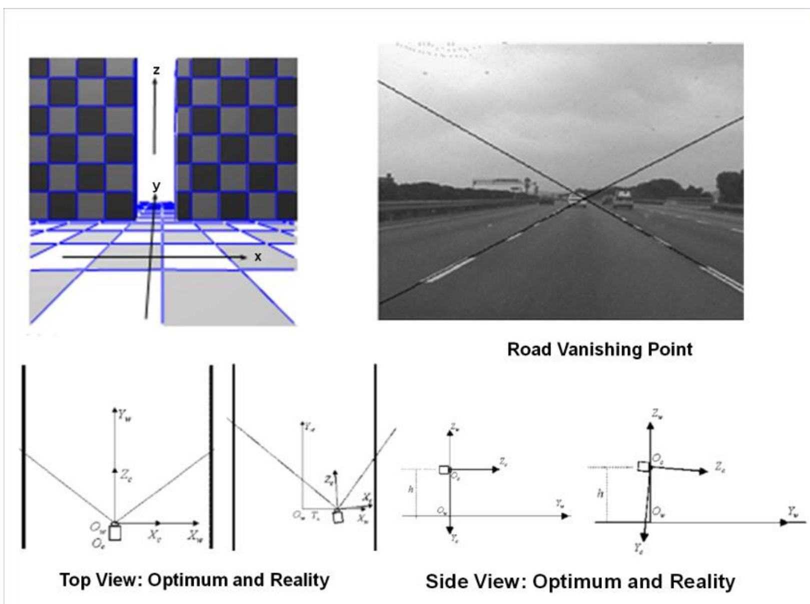


Figure 1.12-2. Image Vanishing Point and Associated Geometry
(Ref: Pflugfelder, R., "Self Calibrating Cameras in Video Surveillance", PhD Thesis, Graz University, Australia, May 2008; and Liang, Yu-Ming, et al, "Video Stabilization for

a Camcorder Mounted on a Vehicle", *IEEE Transactions on Vehicular Technology*, Volume 53, Number 6, November 2004 [68])

1.12.2 Video Performance Assessment

It is difficult to obtain performance accuracy from manufacturers related to their video target detector/tracker performance. A research report entitled, "Precise Position and Attitude Geo-registration of Video Imagery for Target Geolocation" [26], by Dr. Alison Brown (NAVSYS Corp.) discusses a military system called GI-Eye and its ability to provide target range accuracy of 0.3 m (0.98 ft) to 100 m (328 ft) with a 1 mrad bearing accuracy.

While a video image provides a picture of the target, it is difficult to obtain the center reference location of the target (object). The azimuth and near range boundaries can be determined and will be a function of the sensor pixel resolution in the horizontal axis (around 105 cm (41.3 in) for a 30 deg. FOV at 100 m (328 ft) and 480 pixel horizontal resolution). The aspect of the target may be such that boundaries are not clearly visible. If templates are used for target identification it is possible to develop some assumptions on target geometry from the identification template; however, this would be unsuitable for safety of life decisions.

In research report entitled, "Video stabilization for a Camcorder Mounted on a Vehicle", by Yu-Ming Liang, et al, [27], accuracy was achieved of 0.7% azimuth angle and 0.1% for range. In a technical presentation entitled, "3D Position Measurement Technology" [28], by FujiXerox, it is stated that target (x,y) accuracy of from 0.5 to 3 pixels is obtainable. Assuming 50 meters and 480 pixels, this equates to an error of 52 to 312 cm. A research report by David Llorch, entitled, "Vision Based Traffic Data Collection Sensor for Automotive Applications" [34], found average errors to be 0.5 meters. **Figure 1.12-3** presents a graph of video sensor resolution versus range measurement error for various camera resolutions.

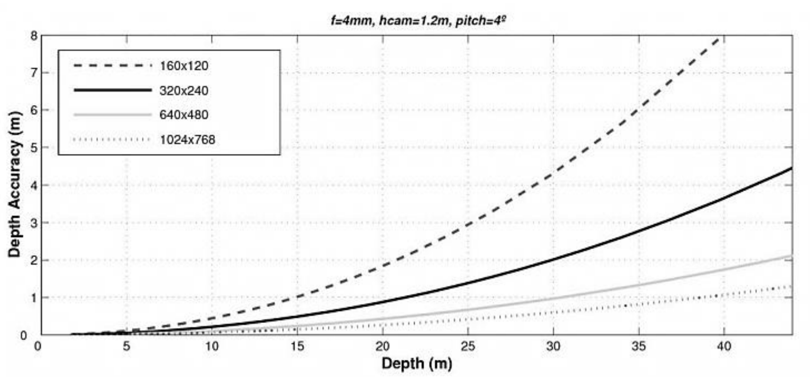


Figure 1.12-3. Range Error versus Range for Various Camera Resolutions
(Ref: "Vision Based Traffic Data Collection Sensor for Automotive Applications", David Llorca, et al, *Sensors,* Volume 10, January, 2010 [69])

In summary, video systems provide a high degree of scene acuity, that is, the ability to differentiate objects in the scene, but they require substantial processing, and are subject to disruption from variations in lighting, shadows and other image related issues. Many of these issues can be addressed through filtering and spectral techniques (what we see as a visual shadow may not appear as such at other wavelengths). Video systems can be very effective with Stereo imaging, but these systems are very sensitive to changes in the camera positions, and as such are challenging to manufacture as consumer products. Currently, video systems represent a substantial augmentation to ranging systems, and there has been substantial progress in fusing the acuity of video systems with the quantitative ranging of ranging systems such as RADAR and LIDAR. As computing capability continues to improve, and as more sophisticated algorithms are developed to insulate these systems from lighting variations, it is expected that stand alone video systems may become more widely used for general detection and modest accuracy ranging.

1.12.3 Deployability Assessment

Video detectors (VIDs) are widely used by jurisdictions to support infrastructure related applications and are reasonably priced for the performance provided. Because VIDs are installed over the roadway they are susceptible to large vehicle masking of the field of view and they are susceptible to weather conditions, roadway lighting, reflections and lane changes by vehicles.

In a Minnesota DOT report entitled, "Evaluation of Non-Intrusive Technologies for Traffic Detection" [29], field tests indicated a count error of 2% and speed error of 2 % was also indicated. A Battelle report entitled, "Advances in Traffic Data Collection" [30], indicates VIDs have a 3-4 % error in count and a 5-6% error in speed. In a research paper entitled, "Vehicle Tracking and Speed Measurement at Intersections Using Video Detection Systems" [31], test accuracy of VIDs is reported to be 7.2% count error and ±5 km/hr (3.1 mph) error. VIDs designed for infrastructure applications are basically designed to emulate inductive loops. They use detection zones which can be positioned within the field of view of the CCTV camera and sized to accommodate corridor geometry and detection objective. Dual detection zones are utilized to determine vehicle speed measurement. When a vehicle reaches the front edge of the detection zone it provides activation and when the vehicle's image clears the detection zone, it is deactivated. The detection signals are interfaced with a signal controller in much the same way as inductive loop detectors. VIDs meet the purpose for which they were designed, which includes gathering traffic statistics, providing calls to traffic signal controllers, detecting queue overflows, and supporting incident detection. Their installation and set-up of detection gates are relative to traffic related reference points, such as stop lines of intersections. While it is possible to geo-reference detection zones based on VID installation location, field of view (based on lens used), and set up of the detection zones within the field of view, it is not generally done. It is the relative location of detection zones (to lanes and stop lines) that is important for the deployed application.

A research paper entitled, “Detection and Classification of Vehicles” [32], discusses the test results of video vehicle detection and tracking. Using a video detector/tracker on a freeway, 90% were detected and tracked; only 70% of those vehicles that were tracked were classified by the video processor. In another research paper related to infrastructure deployed video detectors/trackers, entitled, “Model-Free Video Detection and Tracking of Pedestrians and Bicyclist” [33], the video detector/tracker had an average detection accuracy of 92.7% and in some was as low as 83.3% and never exceeding 94%. PhD thesis at Clemson University by Neeraj Kanhere, entitled, “Vision-Based Detection, Tracking and Classification of Vehicles using Stable Features with Automatic Camera Calibration” [34], indicated that a “boosted cascaded vehicle detector” provided 76% to 82 % true positive detection and tracks and 5% to 13% false positive detections and tracks. Mean speed error was 10%. Single frame video processing required 32 msec; to acquire a video frame and to process the frame required 65 msec (at 30 frames per second). Again, infrastructure mounted video detectors/trackers have the benefit that the camera is not moving and only vehicles and pedestrians are moving. The processing task becomes much more complex if the camera is mounted on a vehicle.

1.12.4 Installation, Test and Calibration

Because they rely in a known/fixed field of view to separate objects of interest from the background, fixed video systems must be calibrated when installed, and must be periodically recalibrated to allow for physical changes in the background, and for shifts in the position of the camera. This calibration can be performed in software, but must be done under controlled circumstances.

Mobile video systems (on vehicles) are much more complex since they need to continuously resolve objects of interested from the background, and the background is always changing. Most current systems in use are special purpose devices used, for example, to sense lane lines. In this application, the camera must be aligned to the vehicle so that the objective position of the lane lines in the field of view corresponds to the desired position of the vehicle between the lines. If this alignment is off, then system will position the vehicle incorrectly in the lane. In a moving vehicle, image stabilization is required.

1.12.5 Applicable Standards

There are several different video standards in use around the world. In the US, the most typical is NTSC. This covers conventional raster video. There are also different signaling formats such as composite, S-Video, and RGB. Composite video is not used much anymore, and S-Video is typically used in DVD players and various consumer playback devices.

RGB is the dominant standard in the computing industry, offering best resolution and quality of image. However, RGB needs at least three high quality cables, four if the separate sync signal is used, which is quite common. In some high end applications (such as workstations) five wires are used, with separate horizontal and vertical drive signals in place of the sync line. In contrast to the single cable of the composite signal or the dual cable of the S-Video signal, this added complexity may be problematic in infrastructure installations. Equipment to process RGB also needs more channels to deal with the separate red, green and blue color signals and either of two sync methods (external or sync on green). All channels in RGB must be equal (high) bandwidth. This is part of why some RGB equipment costs more. Where monochrome imaging is sufficient it may make sense to use the older standards. Most new video cameras have an integrated sensor array/video processor on a single chip. Uncompressed digital video or compressed digital video (MPEG 2, MPEG 4, H.264 and M-JPEG) interfaces can typically be supported.

1.12.6 Cost and Life Cycle Status

Video cameras continue to fall in price. Twenty years ago, a video camera cost over $1000, today almost any cell phone includes a high resolution video capability. Webcams that provide video information to a variety of PC applications are commonly available for under $100. So, the camera technology is in a mature phase and is rapidly becoming a commodity. The area that is less developed and that is likely to see substantial evolution over the next decade is video processing. This is discussed in Section 4.6.7 below.

1.12.7 Technology Evolution and Forecast

The evolutionary force today in video technology for ITS is in image processing. Nearly all of the autonomous vehicles used in the DARPA Challenges used some form of video processing, typically in conjunction with high precision LIDAR ranging in order to interpret the roadway scene. The winning vehicle from General Motors had ten high performance processors dedicated to the task. However, video animation and gaming applications have driven massive improvements in video image processing hardware and algorithms. Advances in processing capability have allowed, and are expected to continue to support, high-performance stereo image processing that is able to use parallax in a moving image field to separate objects. The Microsoft Kinect system uses a combination of infrared ranging and video image processing to pick out an individual in a conventional living room (separating her from other room occupants based on range and position in the field of view; the player typically stands in the center of the room, while other sit and watch). The system uses video processing to identify the individual’s limbs and to track them as the person moves. Figure 1.12-4 illustrates the basic skeleton frame used by the system, which defines 15 nodal points recognized by the system for a typical human body.

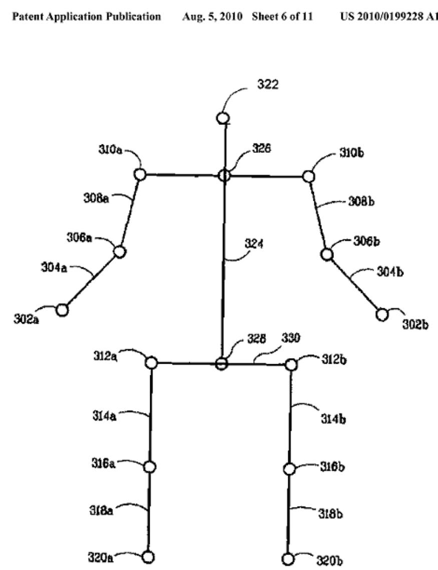


FIG. 4A

Figure 1.12-4 Microsoft Kinect Human Skeleton Nodes
(Ref: US Patent Application 2010/0199228, August 5, 2010 [70])

Figure 1.12-5 shows a sequence of several photos of the Kinect system output [17]. In the upper left image, the person has just walked into the field of view. In the upper right, the Kinect system has identified them as a person, identified their limbs, head, and hands (and also feet, not shown) and created a “stick figure”. In the lower left image the entire stick figure can be seen. In the lower right image, the system is shown as the person turns, foreshortening the arms and placing one hand closer (larger blue dot) than the other. All of this is done in real time, so as the person moves there is typically less than one or two image frames (about 100 msec) [36]. The Kinect box is thus a sensor fusion and video image processing computer that sells in the consumer retail market for about $100.

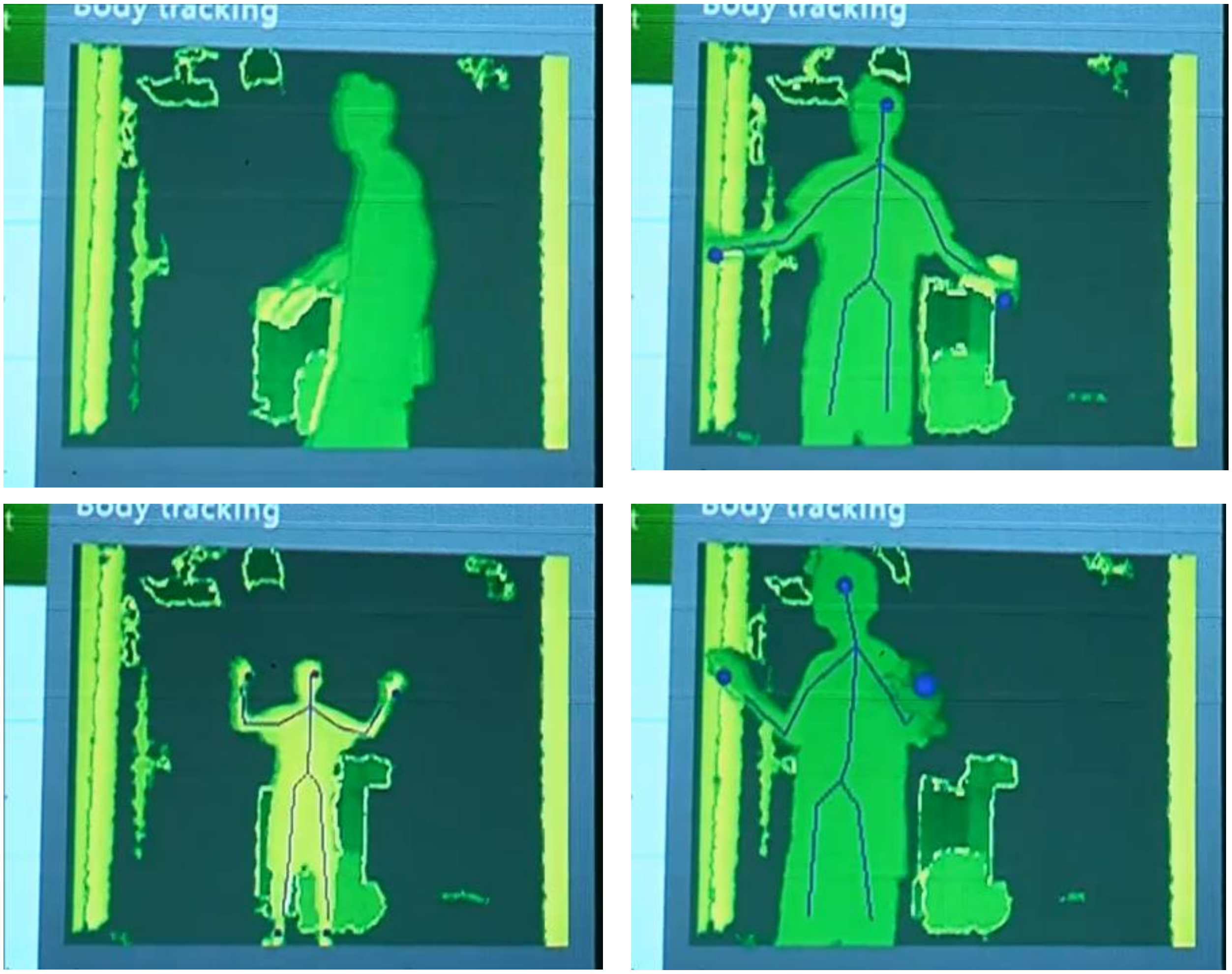


Figure 1.12-5 Microsoft Kinect Figure Acquisition Sequence
(Ref: Code Laboratories;
http://www.youtube.com/watch?v=pk_cQVjqFZ4&feature=related [71])

Clearly more work must be done in this area, but the gains over the past few years have been impressive. It is likely that within a decade this technology will become dominant in all near distance sensing (less than 50 meters).

1.12.8 Video System References

Table 1.12-1. Video References

[19] "Solid or Not Solid: Vision for RADAR Target Validation", by Amir Sole, et al, MobileEye™ Vision Technologies Ltd., 2004.
[20] Porikli, F., et al, "Integrated Detection, Tracking and Recognition for IR Video Based Vehicle Classification", Mitsubishi Electric Research Labs, TR2007-04, 2007.
[21] Premebida, C., "A LIDAR and Vision Approach for Pedestrian and Vehicle Detection and Tracking", IEEE Intelligent Transportation Systems Conference, 2007, September 30, 2007
[22] Keller, C. G., et al, "Dense Stereo-Based ROI Generation for Pedestrian Detection", University of Heidelberg, *Proceedings of the 31st DAGM Symposium on Pattern Recognition*, 2009.
[23] Rranke, U., "From Door-to-Door: Principles and Applications of Computer Vision in Driver Assisted Systems", DaimlerChrysler AG, October 4, 2001.
[24] Betke, M., et al, "Multiple Vehicle Detection and Tracking in Hard Real Time", University of Maryland, Institute for Advanced Computer Studies, presented at *IEEE Intelligent Vehicles Symposium*, 1996.
[25] Haanpaa, D., "Automatic Target Classifier Using Model Based Image Processing", *35th Applied Imagery and Pattern Recognition Workshop* (AIPR'06), October 2006.
[26] Brown, A., (NAVSYS Corp.), "Precise Position and Attitude Geo-registration of Video Imagery for Target Geolocation", *24th JSDE Symposium*, Anaheim, CA, 1998.
[27] Liang, Yu-Ming, et al; "Video Stabilization for a Camcorder Mounted on a Vehicle*", IEEE Transactions on Vehicle Technology*, Volume 53, Number 6, Volume 53, Number 6, November 2004.
[28] Seko, Yasuji, et al (FujiXerox, "3D Position Measurement Technology",*SPPRA '08 Proceedings of the Fifth IASTED International Conference on Signal Processing, Pattern Recognition and Applications*; pp 319-322. 2008.
[29] Minge, E., et al, "Evaluation of Non-Intrusive Technologies for Traffic Detection", MNDOT Report MN/RC 2010-36, September 2010.
[30] Middleton, D. (PhD), et al, "Advances in Traffic Data Collection", Texas Transportation Institute; Jan 31, 2003.
[31] Zong, T., et al, "Vehicle Tracking and Speed Measurement at Intersections Using Video Detection Systems", *ITE Journal*, January 2009.
[32] Gupte, S., et al, "Detection and Classification of Vehicles", *IEEE Transactions on Intelligent Transportation Systems*, Volume 3, No. 1, March 2002.
[33] Malinovsky, Y., "Model-Free Video Detection and Tracking of Pedestrians and Bicyclist", Computer-Aided Civil and Infrastructure Engineering, Volume 24, 2009.
[34] Kanhere, N., "Vision-Based Detection, Tracking and Classification of Vehicles using Stable Features with Automatic Camera Calibration", PhD thesis at Clemson University, August 2008.
[35] What Kinect Sees; http://www.youtube.com/watch?v=pk_cQVjqFZ4&feature=related By: Code Laboratories/NUI
[36] Tech Report: "Kinect - The Latency Question"; http://imagequalitymatters.blogspot.com/2010/08/tech-report-kinect-latency-question.html

Chapter 5 Supporting Positioning Technologies

1.13 Inertial Systems

Dead Reckoning is an integral element of a vehicle's navigation system. It is utilized to estimate the location of the vehicle with loss of a GPS location, to assist in map matching, and to support collision avoidance by projecting the future position of the vehicle based on current position and velocity/acceleration vectors.

In its simplest form the dead reckoning algorithm calculates the position of the vehicle by integrating the traveled distance in various directions in relation to a known position from the GPS determined location and a time reference. The distance traveled from the position/time reference can be measured by wheel sensors and direction is provided by an electronic compass or heading reference unit. In some simple vehicle navigation systems, wheel sensors are used for determining the driving direction by comparing the distance traveled by the left and the right wheel. In the simplest dead reckoning system, the measured distance and direction are not high accuracy and thus error accumulates with distance traveled, with typically 4% being achievable for distance and 1% for bearing.

A commercially available dead reckoning module on the marker has 3 integral gyros, 3 accelerometers, and 3 magnetometers and further includes a GPS interface. It is advertised to provide an accuracy of 1degree in azimuth and a horizontal accuracy of 2% of the distance traveled, using Kalman filtering. Vertical accuracy is specified to be 1.5 meters. The dead reckoning module is very small (2" x 2" x 0.5 ") and weighs 25 g (0.8 oz.). The module uses MEMS technology and provides a position output at a 4 HZ rate.

In a paper entitled, "Development of a High Accuracy Positioning System for Platform Maneuvering" [125], heading accuracy of 0.02deg static and 0.06 deg. Kinematic was obtained with both fiber optic and MEMS IMUs. In a research paper entitled "GPS/Reduced IMU with a Local Terrain Predictor in Land Vehicle Navigation" [126], low cost IMUs achieved around a 1.35 degrees (RMS) heading error and a velocity error of 0.08 m/s (RMS). The error versus time of MEMS and fiber optic gyros is a function of both angular measurement accuracy as well as drift as a function of time.

A research paper entitled, "Parametric Error Equations for Dead Reckoning Navigation in Ground Vehicle Guidance and Control" [127], discusses using a single axis gyro for heading and a Doppler RADAR for velocity. Heading gyro drift errors were reduced by using a multi-antenna carrier phase GPS attitude determination system. Position error caused by heading errors and Doppler RADAR speed measurement errors were reduced by using position and velocity estimate from a differential carrier phase GPS navigation system. Results of field tests indicate that a heading to within +1 deg, and position estimation to within 0.3 m, could be achieved with a 20 to 40 second loss of GPS. Sample rate was identified as a source of position errors.

The European Cooperative Vehicle-Infrastructure Systems (CVIS) initiative and the associated eSAFETY program use the Position and Mapping (POMA) navigation subsystem for the OBU. Figure 1.13-1 illustrates the dead reckoning element of the navigation system. Dead reckoning is basically one navigation element in the current vehicle navigation systems that support map matching and navigation for short periods of time when GPS signals are lost. There continues to be an emergence of MEMS IMU and heading reference units, and three axis accelerometers available on the market.

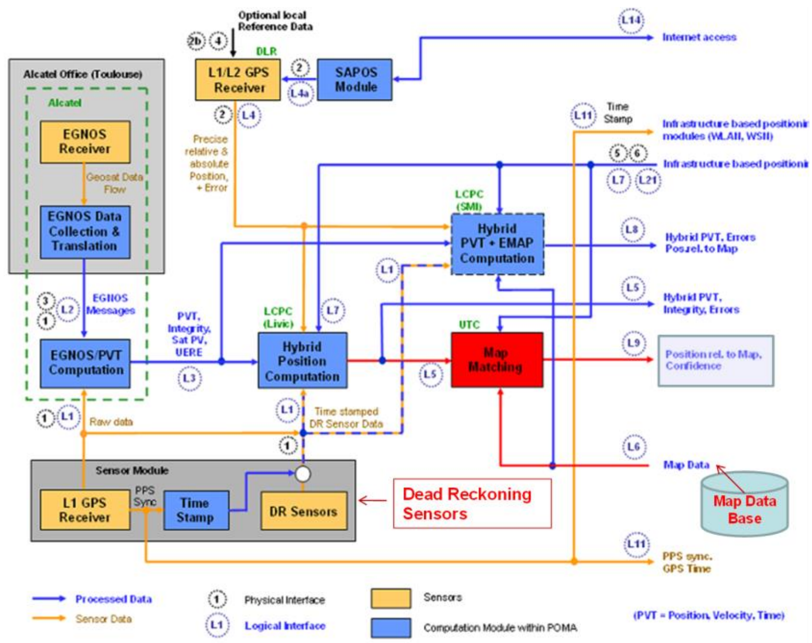


Figure 1.13-1. Positioning and Mapping Subsystem of the European Cooperative Vehicle-Infrastructure System (CVIS) Initiative

(Ref: "Reference Execution Platform", CVIS Project Document D.CVIS.4.1, June 30, 2009 [72])

Figure 1.13-2 illustrates some of the IMU products that are available.

Figure 1.13-2. Examples of Small IMUs and IMU Chips Available on the Market
(Source: Composite of Product Data from Various Manufacturers)

Table 1.13-1 presents a summary of the characteristics of different IMU types. Table 1.13-2 presents a comparison of available integrated IMU products. The small IMUs are not generally maintainable at the component level and must be considered as expendable unit at a vehicle service center. Current MEMS IMU chip cost is around $400 in quantity; these chips have to be packaged and provided with power supply and interface logic. This brings the finished product cost up to over $1000. Because of cost, car manufacturers are currently using only essential components to support dead reckoning. The appearance of attitude related features in smart phones has created a huge new market for various types of inertial sensors, so the cost and capability of these devices is expected to fall rapidly over the next few years.

Table 1.13-1. IMU Types

IMU Categories				
IMU Type	**Navigation Grade**	**Tactical Grade**	**Industrial Grade**	**Hobbyist Grade**
Cost ($)	> 50k	10-20k	0.5-3k	<500
Weight	> 5 lb	About 1lb	< 5 oz.	
Gyro Bias	< 0.1 deg/h	0.1-10 deg/h	≤ 1 deg/sec	>1 deg/sec
Gyro Random Walk Error	< 0.005 deg/root - Hz	0.2-0.5 deg/root - Hz		
Accel Bias	5-10 mg	0.02-0.04 mg		

Source: ARINC April 2012

Table 1.13-2. Comparison of Available IMU Products

Specifications	Product A	Product B	Product C	Product D	Product E	Product F
Size (mm)	41 x 63 x 32	44 x 25 x 11	58 x 58 x33	23 x 23 x 23	28 x 39 12	75 x 75 x 17
Weight (g)	39	18	68	16	6	36
Orientation Accuracy (Static)	±0.5° typical	±0.5° typical	<0.5°(roll/pitch)	Only raw data	N/A	<0.5°(roll/pitch)
Orientation Accuracy (Dynamic)	±2.0° typical	±2.0° typical	1° RMS			<2.0° typical
Update Rate	<100Hz	<1000Hz	<120Hz	<330Hz	<50Hz	<200Hz
Gyro Bias (°/sec)	±0.2	±0.2	1	±3(initial)	N/A	<0.028 (25°C)
Gyro Range (default)	±300°/sec	±300°/sec	±300°/sec	±300°/sec	±300°/sec	±500°/sec
Gyro Nonlinearity	0.2%	0.2%	0.1%	0.1%	1%	<1%
Gyro Random Walk Error	N/A	N/A	0.05°/sec/root-Hz		N/A	N/A
Accel Bias	±0.005g	±0.005g	±0.002g	±0.05g (initial)	N/A	±0.0005g(X,Y) ±0.0016g(Z)
Accel Range (default)	±5g	±5g	±50m/s^2	±18g	±3.6g	±2g
Accel Nonlinearity	0.2%	0.2%	0.2%	0.1%	0.3%	<0.5%
Mag Bias (Gauss)	±0.01	±0.01	0.0001	±0.004	N/A	±0.000125
Mag Range (Gauss)	±2.5	±1.2	±0.75	±2.5	N/A	±6
Mag Nonlinearity	0.4%	0.4%	0.2%	0.5%	N/A	<1%

Source: ARINC April 2012

Figure 1.13-3 illustrates the IMU axis that must be aligned. The technical report entitled, “Developing an Inertial Navigation System for Guidance and Control of Underwater Vehicles” [128], discusses IMU installation alignment and calibration in a vehicle. A major IMU manufacturer’s installation manual provides the following cautions:

- Vibration can make the accelerometer readings noisy and if the magnitude exceeds accelerometer range, outputs become saturated and results in errors. The unit must be installed in a manner to reduce vibrations;
- EMI can cause bias shift of rate sensors; IMU should be installed in a location not susceptible to EMI;
- IMU operation with extended maneuvers causing IMU sensors to operate close to maximum range can result in large errors due to scale factor errors of the rate sensors;
- Exceeding the maximum range of the rate sensors can cause saturation and over-range condition will result in corrupted data during and just after recovery.

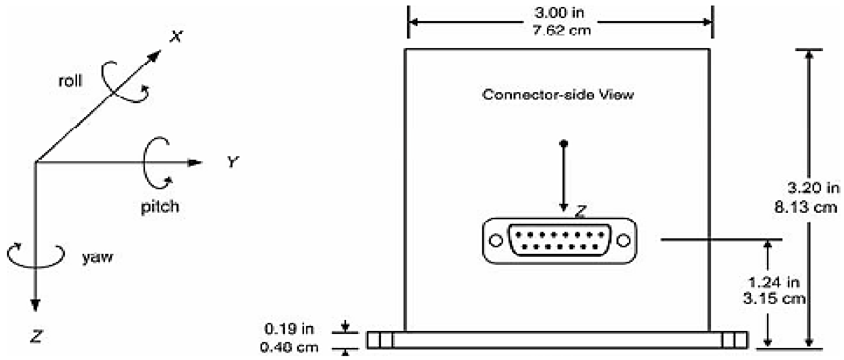


Figure 1.13-3. Example of IMU Reference System Which Must be Aligned to the Axis of the Vehicle in Which it is Installed
(Ref: Major IMU Manufacturer's Installation Manual)

Other technical references related to IMU installation and calibration are listed in Table 1.13-3.

Table 1.13-3. Target Tracking References

[109] Skog, I., Handel, P., "Calibration of a MEMS Inertial Measurement Unit", *Metrology for a Sustainable Development*, September, 17–22, 2006 Rio de Janeiro, Brazil.
[110] Aggarwal, P., et al, "Cost-effective Testing and Calibration of Low Cost MEMS Sensors for Integrated Positioning, Navigation and Mapping Systems", *Shaping the Change XXIII FIG Congress*, Munich, Germany, October 8-13, 2006.
[111] Dorata, A.,et al, "Driving the Line", *GPS World*, March 2003.
[112] Kuga, H.K., et al, "Experimental Static Calibration of an IMU Based on MEMS", *Proceedings of the 19th International Congress of Mechanical Engineering*, November 5-9, 2007.

1.14 Hybrid GPS/IMU

The Inertial Measuring Unit enhances vehicle navigation by providing a continuous measurement of position, velocity and acceleration. As discussed in the IMU section, drift causes IMU measurements to provide an increase in error versus time. In addition, the IMU cannot actually determine its location; it can only determine changes in position from a known starting location. So an IMU must be initialized at a known location. By using GPS to provide this position, the IMU can be effectively calibrated at each GPS epoch. This means that IMU drift error is typically only relevant over the 250 msec to 1 second position update rate of the GPS. With loss of GPS coverage so that GPS is unable to provide a usable position estimate (i.e. less than 4 satellites, or poor integrity), the IMU can then provide position estimates until the GPS position is regained, or until the drift of the IMU renders any estimated position unusable. The quality of the IMU determines the rate at which the system will accumulate position error over time in the absence of GPS position updates.

In a hybrid IMU/GPS system, the inertial measurement of motion is combined with the measured absolute position. The way in which the GPS and inertial position estimates are coupled can have a large impact on the overall accuracy of the system. In the simplest systems the IMU is simply updated at each GPS epoch. The position output is thus the inertially estimated position since the last GPS update. If the GPS system is unable to provide an update the IMU "coasts", providing continuous estimates based on the last known GPS position and the inertial measurements since the last GPS estimate. This type of hybrid system is effectively not coupled, since the measurements from the two systems are not used together at the same time.

In coupled systems, the inertial and GPS solutions are merged to form a true hybrid position solution based on a mathematical coupling that has specified error objectives. Generally the coupling mechanism is a Kalman filter, which "blends" the various parameters from the two systems in a way that minimizes the overall error. Typically the Kalman filter is used to predict the vehicle position based on dynamic measurements that are used in a model of the vehicle motion. So, for example, the position of the vehicle might be predicted based on speed, heading, acceleration, and yaw rate as measured by inertial sensors. The actual position measured by GPS is then compared to the predicted position, and using the known error models for the measurements, the lowest probable error solution is computed. This position is typically a combination of the predicted position and the measured position. A convenient feature of the Kalman filter is that it makes the optimal use of the two types of measurement. Inertial errors tend be very smooth and uniform, but also tend to drift over the longer term,, so the estimated position from moment to moment is highly representative of the actual vehicle motion, but over long time frames small errors in each successive measurement will accumulate and produce a large error in the position estimate over time. In contrast, GPS measurements are never particularly far from the actual position, but successive estimates may "jump around" due to random error in the pseudorange measurements. The Kalman filter uses these two different error models to produce a position estimate that is stable and relatively noise free in the short term, and relatively accurate over the long term.

The quality of the IMU determines the amount of error in navigation information versus time. However, different GPS-IMU coupling techniques and fusion algorithms, improves performance. There are generally three basic coupling architectures:

- Loosely Coupled;
- Tightly Coupled;
- Ultra Tightly Coupled.

A loosely coupled system simply computes position based on GPS and then refines this position based on the inertial measurements. Effectively the inertial measurements are used to validate and correct the GPS position estimate.

The tightly coupled system uses a motion model that combines pseudoranges and inertial elements to estimate position.

The ultra-tightly coupled system uses a more sophisticated model to predict and correct the changes in pseudoranges. These corrected or refined pseudoranges are then combined with the inertial measurements to estimate the position.

These architectures are shown in Figure 1.14-1.

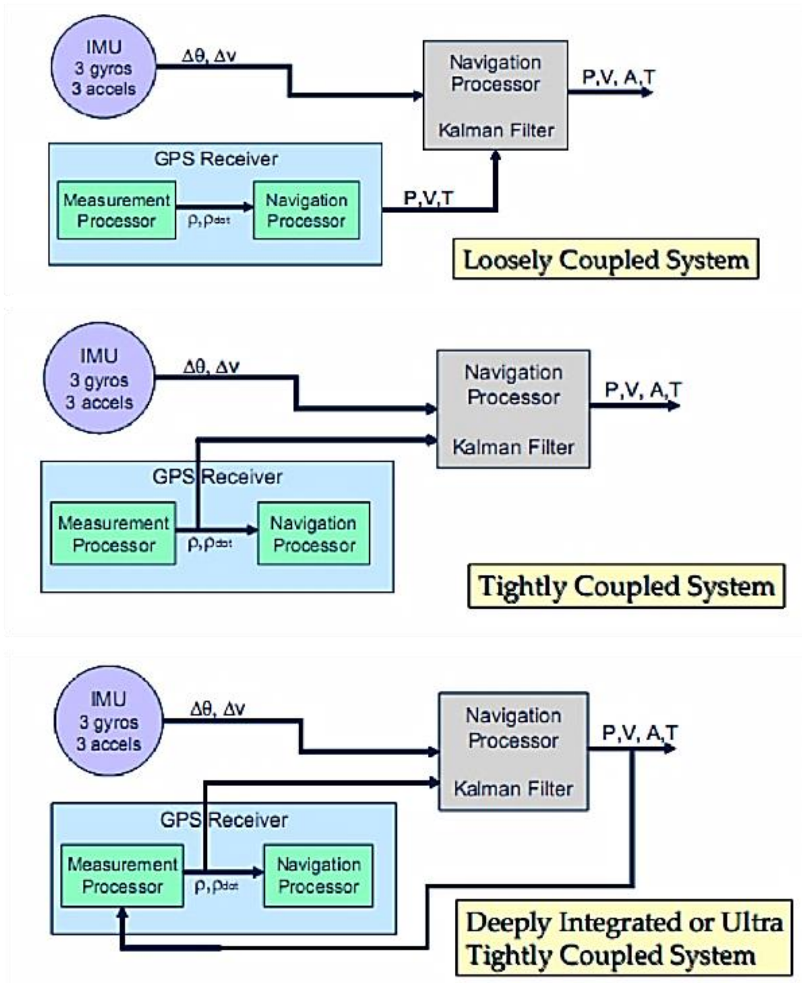


Figure 1.14-1. Examples of Loosely, Tightly, and Ultra Tightly Coupled GPS-IMU Architectures

(Ref: Gautier, J., "GPS/INS Generalized Evaluation Tools for Design and Testing of Integrated Navigation Systems", PhD Thesis, Stanford University, June 2003 [74])

There are a number of Kalman Filters used for both the IMU and GPS functions as well as the coupling function. An Extended Kalman Filter (EKF) and Sigma-Point Kalman

Filter SPKF) are two newer approaches as well as Adaptive Kalman Filters (AKF) and Artificial Intelligence AKF (AI-AKF). Also Fuzzy Logic filters have been used. Sensor integration provides more accurate states (position, attitude, velocity, etc.) that support generation of a more accurate navigation solution.

The comparative performance of the SPKF versus the EKF, which is currently used in many integrated navigation systems, is shown in Figure 1.14-2 based on test conducted at Ohio State University (Ref: Wan, E., et al (Ohio State University), "Sigma-Point Kalman Filter Based Integrated Navigation System", Proceedings of the 60th Annual Meeting of The Institute of Navigation; June 7 - 9, 2004 [95]).

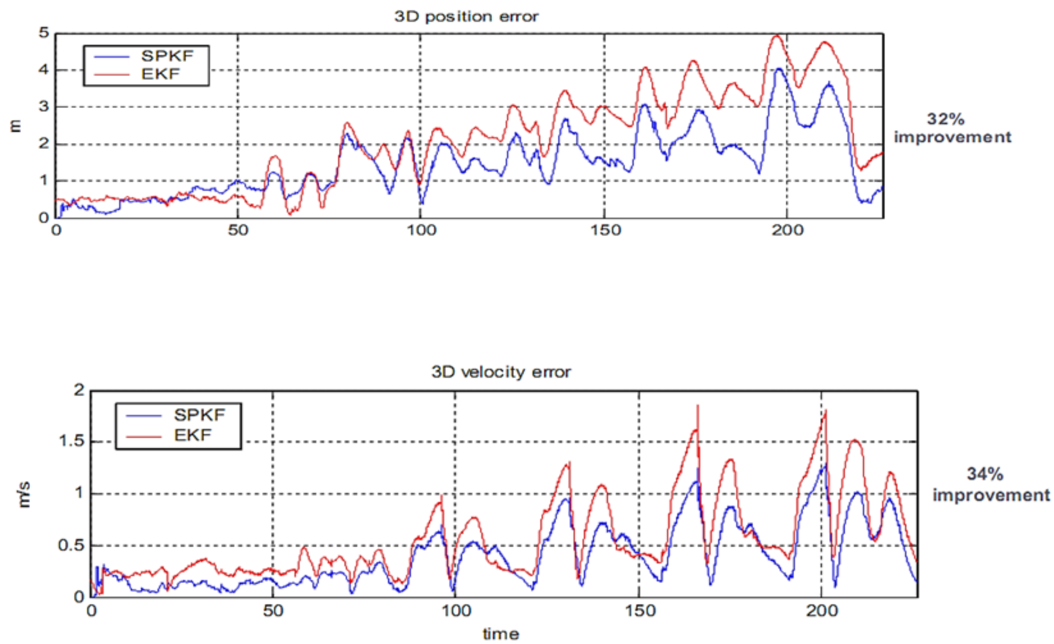


Figure 1.14-2. Comparative Performance of SPKF and EKF with GPS Outage (time –sec; improvement vs. Extended Kalman Filter)

(Ref: Wan, E., et al (Ohio State University), "Sigma-Point Kalman Filter Based Integrated Navigation System", *Proceedings of the 60th Annual Meeting of The Institute of Navigation;* June 7-9, 2004 [75])

Research report entitled, "Intelligent MEMS INS/GPS Integration for Land Vehicle Navigation" [37], discusses AKF and AI-AKF filters used with low cost MEMS GPS/IMUs. The author published continued research accomplishments in an article entitled, "Improving Adaptive Kalman Filter in GPS/SDINS Integration with Neural Network" [129]. The AKF provided a 28% improvement in positioning accuracy as compared with the standard filter used in the test GPS/IMU product and a 44% improvement using the AI-AKF.

In research report, "Sensor Fusion for Robot Navigation using a Fuzzy-EKF with Weighted Covariance" [38], the development of a Fuzzy EKF is presented and comparative test using a GPS/IMU with a standard EKF filter. The conclusion of this research report was that the Fuzzy-EKF provided an improved accuracy of 4 to 5.75 times that provided by the EKF filter; however, it took 1.936 times longer to compute. The report recommended development of a "double Fuzzy EKF that would be added to literalize inputs and would be an alternative to standard Jacobian linearization used in standard EKF. Ahmed Hasan, et al (University of Malaysia) published research in adaptive Neuro Fuzzy Filters in research paper, "Integration of GPS and INS with Differential Sampling Rate using Adaptive Neuro Fuzzy Interference System" [39], which indicated that the Neuro Fuzzy filter provided a 20% improvement positioning accuracy compared with a standard Kalman filter.

Research paper entitled, "High-Integrity IMN-EKF-Based Road Vehicle Navigation with Low-Cost GPS/SBAS/INS" [40], presents test results of test using an Unscented Kalman Filter (UKF), Extended Kalman Filter (EKF), and Interactive Multimodal Methods Extended Kalman Filter (IMM-EKF). With a 50 sec. GPS outage, the UKF solution provided a 4.52 m RMS position, the EKF provided a 4.51 m solution and the IMM-EKF solution provided about the same performance (4.2 m RMS with 42 sec GPS outage). The GPS unit used in the test was specified to provide a single point L1 solution of 1.8 m (5.9 ft.) CEP; a single point L1/L2 solution of 1.5 m (4.92 ft.) CEP; a single point SBAS L1 solution of 1.2 m (3.94 ft.) CEP; and an SBAS L1/L2 solution of 0.8 m (2.62 ft.) CEP. The IMU utilized was low cost MEMS.

Hybrid positioning systems are generally well established for in-vehicle systems. However, the predictive models used to drive these systems can be improved. For example, the carrier smoothed code phase GPS process described in Section 4.1.1.2 is effectively a Kalman filter based system that uses change in carrier phase as one of the predictive elements. Since these techniques (carrier smoothing and hybrid IMU/GPS positioning) have been developed independently, it is likely that further improvements can be obtained by combining these approaches in an integrated way. In such a system the predicted position would be based on the combined inputs from the carrier phase and the inertial sensors. Changes in these measured values should provide a very precise and low noise prediction of the change in vehicle position from one measurement to the next. When then combined with code phase absolute position estimates, the overall position estimate should be very accurate.

Table 1.14-1. Hybrid GPS/IMU References

[37] Wang, J., "Intelligent MEMS INS/GPS Integration for Land Vehicle Navigation", PhD thesis at University of Calgary, September 2006.
[38 Pratt, K., et al, "Sensor Fusion for Robot Navigation using a Fuzzy-EKF with Weighted Covariance", University of South Florida.
[39] Hasan, A., et al (University of Malaysia), "Integration of GPS and INS with Differential Sampling Rate using Adaptive Neuro Fuzzy Interference System", World Applied Science Journal, Volume 7, 2009.
[40] Toledo-More, R., et al, "High-Integrity IMN-EKF-Based Road Vehicle Navigation with Low-Cost GPS/SBAS/INS", *IEEE Transactions on ITS*, Volume 8, Number 3, September 2007.

1.15 Digital Maps

Digital maps are an integral part of a vehicle navigation system. Positioning systems are generally aimed at helping the vehicle system determine where it is relative to the road, or to a hazard such as an application event point as described in the requirements section of this report.

If the positioning system uses absolute position the system must then have some way to determine the relative position of these other elements (hazards, etc.). Most applications use digital maps of the roadway to relate the estimated position of the vehicle to various roadway elements. By knowing the absolute position of, for example, a limit line, and the absolute position of the vehicle, the systems can determine the relative distance between the vehicle and the limit line.

Some example applications requiring digital maps in vehicles are summarized in Table 1.15-1.

Table 1.15-1. Examples of Applications Utilizing Vehicle Digital Maps
(Ref: eSafety Forum, Digital Map Working Group, "Final Report – Recommendations", November 28, 2005 [76])

Role of the Map as Sensor for Safety Systems	
Primary Sensor	**Secondary Sensor**
Speed Limit Assistance (e.g., Speed Alert): Informs the driver of the legal speed limit at the location of the vehicle and/or warns the driver when exceeding the legal speed limit.	**Advanced Front-Lighting System**: Directs the front light beam in the direction of the turn a car intends to take, or adapts beam width and reach on basis of the vehicles speed and the road lay out.
Curve Warning: Warns the driver when his/her current speed exceeds the safe speed for the curve ahead, and possibly the distance to the curve and the required brake force.	**Adaptive Cruise Control**: Adapts a vehicle's desired speed to the speed of preceding vehicles or road geometry ahead. Adaptive cruise control typically works at higher speeds only.
Predictive Powertrain Control: Informs the system of upcoming slopes thus enabling gear shifts to avoid inefficient speed reduction.	**Lane Keeping Assistance**: Informs the driver when the vehicle is likely to leave the current lane unintentionally.
Intersection Assistance: Informs the driver on intersection characteristics (right of way situation, traffic lights) and which lanes to choose in order to safely traverse an intersection.	**Lane Change Assistance**: Informs the driver when it is safe/unsafe to change lanes.
Curve Control: Automatically reduces the speed of the vehicle to a safe speed for an approaching curve.	**Stop & Go**: Adapts the vehicle's speed and course on basis of a desired speed to the speed of preceding vehicles. Stop & Go typically works at lower speeds.
"Hotspot" Warning: Informs the driver about a potentially hazardous location ahead.	**Collision Avoidance**: Adapting the vehicle's speed and direction of travel in order to avoid a collision.

The use of digital maps raises an important issue, however. In applications where the location of the vehicle relative to roadway elements is critical, the overall allowable positioning error must be allocated between the digital map and the vehicle positioning system. It does little good to have a vehicle positioning system with an accuracy of 1 meter, if the corresponding digital map is only accurate to 10 meters. While the vehicle will be able to determine its absolute position accurately, it will be unable to determine its position *relative to roadway elements* to an accuracy better than 10 meters.

The Task 2 market scans report developed under this project provided a review of digital map accuracy and trends. The European PReVENT project's report, "Safety Digital Map Requirements" (Report PR-12310-SPD-040607-V10-TEL) [41], states that next generation digital maps should have 5 to 15 meter (90%) accuracy. The PReVENT project MAPS&ADAS initiative established the following future map objectives for features and attributes (location to 90% confidence):

- Speed Limit: 1-5 meters;
- Traffic Signs: 1-5 meters;
- Traffic Lights: 1-3 meters;
- Lane Width: 0.3 meters;
- Lane Driven Information: 0.3 meters;
- Pedestrian and Bicycle Crossing: 1-5 meters;
- Accident Hot Spots: 1-5 meters;
- Speed Humps: 3 meters.

The European PReVENT Project, MAPS&ADAS subproject specifications for digital maps are published in the following documents:

- D12.31 Safety Digital Maps Requirements;
- D12.41 Specification and Exchange Format of Safety Related Map Information;
- D12.41 Specification and Exchange Format of Safety Related Map Information;
- D12.5 - MAPS&ADAS - Data Sourcing;
- D12.6 Certification and Business Model;
- D12.71.1 Implementation Environment Description and Specification;
- D12.71.2 Driver Warning System Use Cases and Specification.

The European Road Transport Telematics Implementation Coordination Organization (ERTICO) has established an objective for the next generation maps to have accuracy of 4 meters or less (90%). Finland's DigiROAD® project produced digital maps with accuracies of 3 meters for center line and 5 meters for attributes. The NHTSA Enhanced Digital Mapping Project (EDMap) Final Report (Nov. 2004) [42], states the requirement for centerline map accuracy of 30 cm and a roadside sign attribute accuracy of 10 meters. Minnesota DOT developed digital maps with 20 cm accuracy for supporting snow removal equipment guidance (Ref: Trach, W. Jr, et al, "Final Report - Driver Assistive System for Rural Applications", MnDOT, Report MN/RC-2005-30, August 2005 [43]). The MnDOT report estimates a cost of $10/mile for developing the digital map. Ohio State University, Center for Mapping has developed 10 cm accuracy digital road maps using their GPSVan™. In a report by Stefan Schroedl of Daimler Chrysler, entitled, "Mining GPS Traces for Map Refinement" [44], tests of NavTech digital maps against true centerline indicated a 15 meter error. In a report entitled, "Digital Map Requirements for AVL", by Dr. Joshua Greenfield [45], test results on New Jersey corridors indicated that the NavTech digital map had an accuracy of approximately 30 feet (95%). Research report entitled, "Creating and Evaluating Highly Accurate Maps with Probe Vehicles" [46], development of corridor center line to 0.2 meter accuracy was demonstrated and center lines in both directions of travel are recommended when survey accuracy of 1 meter or less is achieved. The report concludes that Vehicle positioning accuracy within the next 10 years will be sub-meter and higher accuracy corridor centerlines will be necessary to support ITS applications.

In a research report by Pi-Ming Cheng of the University of Minnesota, entitled, “Evaluation of Digital Maps for Road User Charging Applications” [47], it is suggested that the maximum error in a digital map should be no more than 4 meters/90% which is based on a road with two lanes each of 7.3 meters and a co-location distance of 15.2 m and using the formula:

> Separation distance between two roads in opposite directions, S = co-location distance – ½(Road 1 Width) - ½(Road 2 Width), where the road width includes all lanes captured by the road and its centerline. The maximum allowable map positional error (E) is:
>
> E+ ½ (S)

In summary current digital map technology utilized in vehicles has a ground truth accuracy of approximately 15 meters/90%. Higher accuracy digital maps are achievable with modern surveying technology and supporting sensors. Jurisdictions are transitioning to higher accuracy survey of corridors and infrastructure deployed along corridors because of the benefits, such as mobile survey and inspection of assets and automated guidance for public works vehicles 9such as snow removal). Map accuracy impacts errors associated with automatic notification of drivers related to corridor hazards warnings and speed warnings as well as support for intersection safety. The technology to improve corridor map accuracy is available; the issue is cost of survey and building new, improved digital map databases.

While it is feasible to obtain 20 cm center lane accuracy, currently only special developed digital maps, such as those developed by MnDOT to support snow removal equipment guidance, are available. Private suppliers are currently focusing on expanding their map coverage in areas that have not been surveyed and surveying safety features and commercial points of interest to drivers and adding these to their digital maps. Also with roadway geometry and associated infrastructure changing perhaps at a 15% rate per year, resurvey is necessary.

It is also important to differentiate what is commonly thought of as the “map database” and other types of map related information. A good example of this is the geometric intersection description, or GID. The GID is a data file containing precise geometric information about the lanes and limit lines for an intersection. Using this information a vehicle can determine where it is relative to particular elements of the intersection that are relevant to it. The GID for a complex intersection can be extensive, indicating different limit lines and entry points for different lanes, and relating these elements to other message content that might, for example, convey the signal timing for specific lanes.Figure 1.15-1 illustrates the characteristics of the GID.

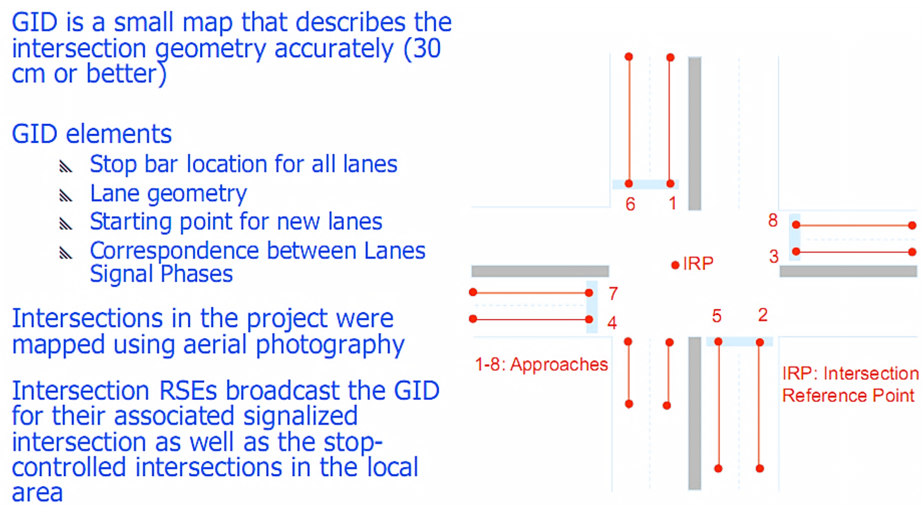


Figure 1.15-1. Characteristics of the SAE J2735 Describing a Signalized Intersection
(Ref: Maile, M., "V2V and V2I Communications Based Safety Applications", SAE presentation, 2010 [77])

Within the MAP (GID) message, the positional 3 dimensional entity describes the precise location of two different nodes within or in the vicinity of the intersection:

- The reference point of the intersection (usually the center of the intersection);
- The reference point of an object (e.g., vehicle) within the vicinity of the intersection.

Latitude – The latitude is expressed in 10^{th} of micro degree and range from – 90^o to + 90^o, thus, 0x-900000000D to 0x900000001D. This integer (in hex) is contained in 4 octets where the least significant bit (lsb) represents 1/10 of a micro degree. With a resolution of a 10^{th} of a micro degree, the distance resolution is in the sub-meter range (e.g., "A micro degree of latitude is about 0.11 meters);

Longitude - The longitude is expressed in 10^{th} of micro degree and range from -180^o to $+180^o$, thus, 0x-1800000000D to 0x1800000001D. This integer (in hex) is contained in 4 octets where the least significant bit (lsb) represents 1/10 of a micro degree. With a resolution of a 10^{th} of a micro degree, the distance resolution is in the sub-meter range (e.g., "0.84° is approximately 50 km at 50° Latitude" translating to 1 micro degree is about 0.06m at 50^o Latitude.);

Elevation – The elevation is expressed in cm and range from 0 to 6143.9 m above the reference ellipsoid, thus 0x0000H to 0xFFFFH. It also encodes elevations from -409.5 to –0.1 m below the reference ellipsoid, thus 0xF001H to 0xFFFFH. This integer (in hex) is contained in 2 octets where the least significant bit (lsb) represents 10 cm (resolution).

As maps for advanced vehicles emerge, they may contain semi-permanent information on road geometry, safety areas of concern along the corridors, “yellow page” locations, etc. There also may be temporary entries related to long term road construction and shorter term appendages relating to road construction that last perhaps a few days or weeks and current road conditions (incidents, ice, flooding, special event, etc.). The semi-permanent information would normally be part of the basic vehicle equipment; however, short duration data most likely will be transferred to the vehicle database using wireless links.

This raises several important issues. First is the ongoing management of map related updates. For example, at what point does a “temporary” map element expire? In addition, any map information used (permanent or temporary) will need to be authenticated and validated. Hacking the map database could be just as effective as hacking the GPS system. So, while today map data is assumed to be correct, as it becomes more widely used for safety related applications it will be necessary to secure the data and provide mechanisms for validation and authentication.

Current private map supplier business models include expanding survey coverage to areas that have no digital maps and to survey locations of safety attribute of corridors (such as speed limit changes, curves in corridors with maximum safe speeds, intersection stop locations, etc.). It will be most likely 5 to 10 years before digital maps of cities are re-surveyed with high accuracy survey equipment and this will only occur if the business case supports profitability or the new, high accuracy survey. Some of the challenges to be overcome related to digital map development and servicing include:

- Periodic update of maps (Tele Atlas indicates that a minimum of 10 to 15% of the road infrastructure changes in a year);
- Distribution of new digital map data bases to users;
- Cost of map data base updates and associated business case;
- Quality Assurance over digital map data bases assuring that standards are met;
- Dynamically identifying to a driver that his digital map does not currently represent changes to the road infrastructure on which he is traveling.

Quality assurance will be an important aspect of digital maps and will require qualification to standards and to:

- Correctness: All map layers are correct and standards compliant
- Accuracy: Accuracy of center lines, corridor boundaries, stop lines, safety attributes, etc., comply with standards;
- Availability: Available in form required by navigation system interface standards and data base standards;
- Up-to-Date: Represents current configuration of corridors included;
- Completeness: Included all data required by standards;
- Reliable: Includes features to prevent corruption.

For example, the authorities responsible for the intersection design, construction, operations, and maintenance will need to also be responsible for providing the GID data to accuracies required by the user applications. Both quality assurance and configuration management will be required. It is envisioned that an index identifying intersections and the correct version of the GID message representing current intersection configuration will be necessary. With this index, an OBE can validate that it has the latest GID version that represents the current geometric configuration of the intersection.

Figure 1.15-2 represents a possible approach for managing the quality and correct versions of GIDs (similar to but not identical, to that used related to National Transportation Communications for Intelligent Transportation Systems protocol (NTCIP) testing and validation).

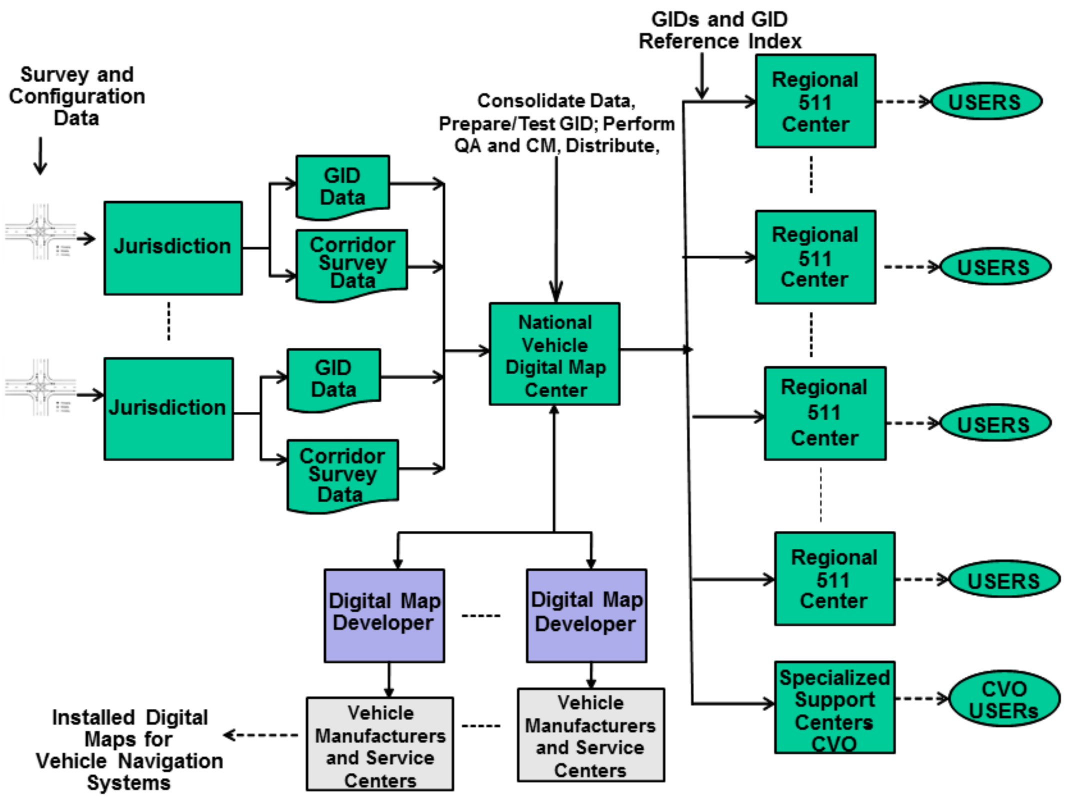


Figure 1.15-2. Possible Approach to Developing and Updating Geometric Intersection Descriptions with Quality assurance and Configuration Management

Source: ARINC April 2012

In summary, GID message development will be an ongoing process as jurisdictions modify existing intersections, add signalization to existing but non-signalized intersections and construct new signalized intersections. GID messages must be error free and represent the current geometrics of the intersection. This will require a formal process to be established for the development, distribution, management, quality assurance and configuration assurance of GID messages.

Maps used in ITS centers should be consistent with maps used in vehicles. While it is not necessary that icons utilized in ITS centers match those used in vehicles, it is appropriate to have a common set of icons for ITS centers to support interoperability. Icons representing safety areas of concern along a corridor should have equivalent accuracy as those used on vehicle digital maps. Intersection diagrams utilized in ITS centers must be fully compatible with those used in the GID messages to vehicles. A quality assurance procedure and digital map update procedure for ITS centers should be part of the overall quality assurance procedure developed for digital map development, distribution and use in applications.

Table 1.15-2. Digital Map References

[41] "Safety Digital Maps Requirements", PReVENT Report PR-12310-SPD-040607-V10-TEL, September 2004.
[42] "NHTSA Enhanced Digital Mapping Project (EDMap) Final Report", November 2004.
[43] Trach, W. Jr, et al, "Final Report - Driver Assistive System for Rural Applications", MnDOT, Report MN/RC-2005-30, August 2005.
[44] Schroedl, S. (Daimler Chrysler), "Mining GPS Traces for Map Refinement", Data Mining and Knowledge Discovery 9, pp. 59–87, 2004.
[45] Greenfield, J. (PhD, "Digital Map Requirements for AVL", The National Center for Transportation and Industrial Productivity; New Jersey Institute of Technology, December 1998.
[46] Rogers, S., et al, "Creating and Evaluating Highly Accurate Maps with Probe Vehicles", IEEE Conference on Intelligent Transportation Systems, 2000.
[47] Cheng, P., "Evaluation of Digital Maps for Road User Charging Applications", University of Minnesota, August 2004.
[48] Society of Automotive Engineers, "SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary", 2009.

1.16 Map Matching

Map matching is a basic component of route guidance systems and has been used since the emergence of GPS positioning in vehicles. Maps are a fundamental way that the guidance system communicates with the driver via the HMI, and are critical to relating the position of the vehicle in absolute coordinates to roadway elements such as intersections, curves and, in some applications (as described above in Section 5.2) critical geometric aspects such as limit lines and lanes.

Map matching is the technique of correcting the estimated position of the vehicle as reported by the positioning system by comparing the path of the vehicle to the road path as defined by the digital map. Conceptually, the approach relies on the fact that the vehicle is expected to be driving on the road, so if the position estimate reported by the positioning system places the vehicle, for example, inside a building, then the reported position must be incorrect. Because it is only based on the assumption that the vehicle is driving on the roadway, map matching is generally oriented toward navigation applications. In this case the need for high positional accuracy is relatively low, but the need to present a rational picture to the consumer is rather high. Consumers would consider a navigation system that showed the vehicle driving through a park or a building as flawed, so the simplest solution is to put the image of the vehicle back on the nearest road.

The simplest approach is to project the estimated vehicle position to the closest road segment, and assume that this is actually where the vehicle is. This approach often fails in situations where two road segments run close in parallel (e.g., a frontage road), to where one road is elevated and runs in parallel with a road below it.

In a research report entitled, "Evaluation of Digital Maps for Road User Charging", by Pi-Ming Cheng [47], the following equation is offered for determining map accuracy needed to support map matching related to two parallel roads. Figure 1.16-1 illustrates the road geometry related to the equations, which follows:

S, Separation Distance = Co-location Distance – ½ (Road #1 Width) – ½ (road #2 Width);

E, Maximum Map Error = ½(S);

For two parallel, dual lane roads, each of a width of 7.2 meters (24') and a co-location distance of 15.2 meters (50'), S = 8 m and E = 4 m (13'). Since many of the digital maps have an accuracy of 15 to 30 meters, it can be seen the difficulty that a map matching algorithm will have defining a parallel road in the same direction (such as a frontage road to a freeway). A simple map matching flow chart is illustrated in Figure 1.16-2 and shows the process of matching a navigation sensor position (GPS or GPS/IMU) to a road segment on a map.

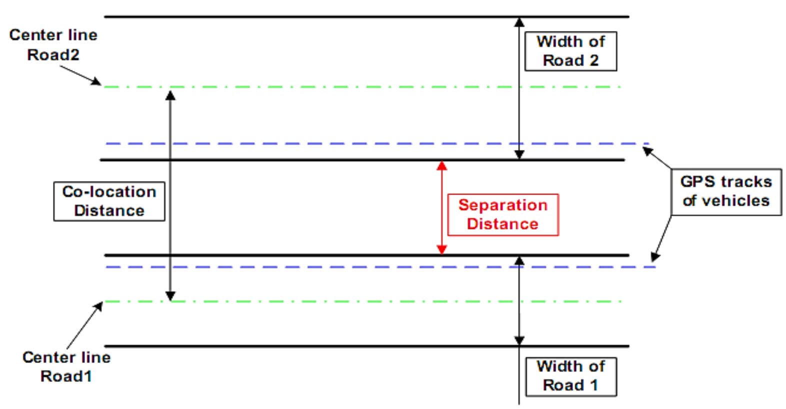


Figure 1.16-1. Parallel Road Geometry and Separation Distance Utilized to Determine Map Accuracy for Map Matching

(Ref: Cheng, P. (University of Minnesota), "Evaluation of Digital Maps for Road User

Charging", MNDOT Report Mn/RC 2003-38, 2003 [78])

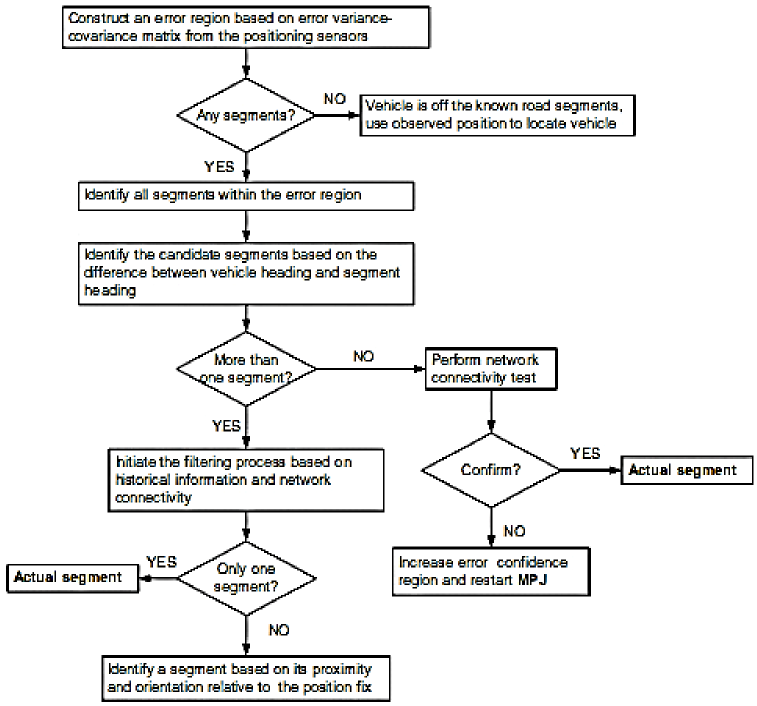


Figure 1.16-2. Flow Chart of a Map Matching Process
(Ref: Loannis , K. (University of Crete), "A Map Matching Algorithm for Car Navigation Systems with GPS Input", *10th AGILE International Conference on Geographic Information Science 2007*, Aalborg University, Denmark [79])

More sophisticated map matching algorithms compare the historical path of the vehicle position estimates to the road geometry, and then decide which road the vehicle must be on. So, for example, if the vehicle has followed a cloverleaf onramp to enter a freeway, then the navigation system can assume that the vehicle is on the freeway, and if a position estimate indicates that it is closer to the frontage road, the navigation system may choose to ignore that position estimate, or at least use only the portion of it that maintains the vehicle on the original roadway.

In a few situations, where the map detail is reasonably high, matching path geometry to the map can substantially improve over all positioning accuracy. For example, vehicles do not typically make right turns into buildings, so if the vehicle does make a right turn (as sensed by the gyro in the dead reckoning system, for example), then the position may be updated to correspond to the nearest corner with an appropriate geometry.

Table 1.16-1 presents references to map matching algorithms match and performance achieved through testing and simulation.

Table 1.16-1. Performance of Map Matching Algorithms
(Ref: Quddus, M., “High Integrity Map Matching Algorithms for Advanced Transport Telematic Applications”, Doctoral Thesis, Imperial College of London, January 2006 [80])

Map Matching Algorithm	Correct Link Identification (%)	Horizontal Accuracy (2σ, m)	Along-track Errors (2σ, m)	Cross-track Errors (2σ, m)
Point-to-Point Matching Bernstein and Kornhauser (1998)	70.5	46.0	45.2	10.3
Point-to-Curve White, et al. (2000)	76.8	32.0	29.5	10.1
Enhanced Point- to- Curve Srinivasan, et al. (2003)	80.2	21.2	18.3	10.3
Topological Matching Greenfeld (2002)	85.6	18.3	15.5	8.6
Turn Restriction/KF Xu, et al. (2002)	86.3	19.5	19.1	6.9
Evidence Theory/KF Yang, et al. (2003)	82.5	25.0	24.1	7.2
Hybrid Fu, et al. (2004)	80.5	23.0	22.0	8.5
Fuzzy Logic/Fuzzy Interference Syed and Cannon (2004)	92.5	16.1	15.1	5.1
Topological Quddas (2006)	88.6	18.1	17.6	4.8
Probabilistic Quddas (2006)	98.1	9.1	8.2	4.0
Fuzzy logic Quddas (2006)	99.2	5.5	4.2	3.2

Fuzzy Logic map matching algorithms have been shown to have good performance. Figure 1.16-3 illustrates results of the fuzzy logic algorithm developed by Mohammad Quddus (Ref: Quddus, M., “High Integrity Map Matching Algorithms for Advanced Transport Telematic Applications”, Doctoral Thesis, Imperial College of London, January 2006 [80]). The multi-hypothesis map matching (MHMM) algorithm is used in the European safety and SAFESPOT initiatives under the Position and Mapping (POMA) development project. Figure 1.16-4 illustrates the system components that support POMA map matching. Tests indicate good performance of the POMA MHMM map matching algorithm as documented in the report, “Lane-level Positioning for Cooperative Systems Using EGNOS and Enhanced Digital Maps”, by F. Peyet, et al., Laboratoire Central des Ponts et Chaussees, Bouguenais, FR [131]. POMA field test which included augmented GPS and dead reckoning sensors indicates that the integrated system will meet the automated driver assist system navigation requirements.

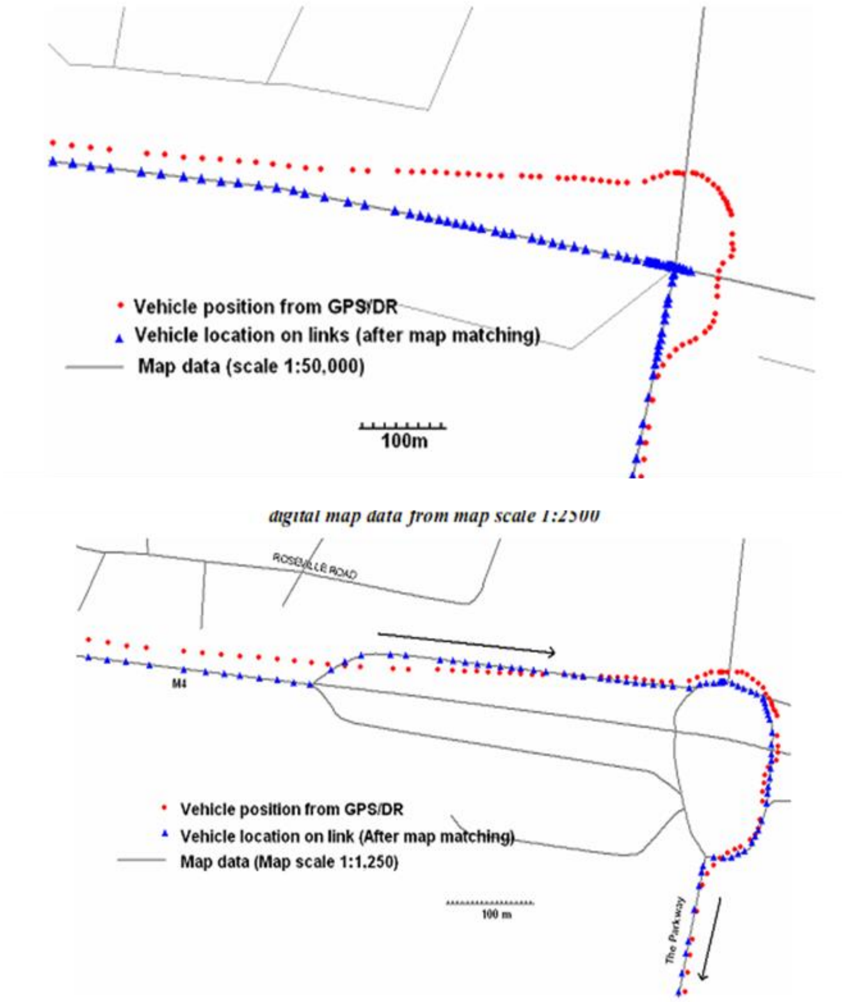


Figure 1.16-3. Example of the Performance of a Fuzzy Logic Map Matching Algorithm

(Ref: Quddus, M., "High Integrity Map Matching Algorithms for Advanced Transport Telematic Applications", Doctoral Thesis, Imperial College of London, January 2006 [80])

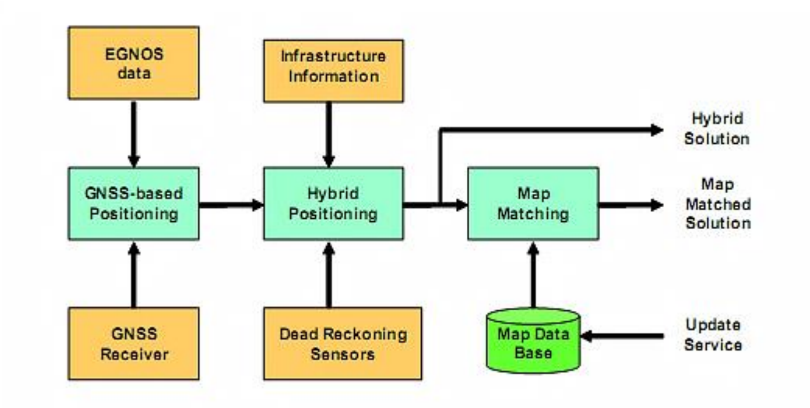


Figure 1.16-4. System Diagram of the European POMA Map Matching Elements
(Ref: Bonnifait, et al, "Multi-Hypothesis Map Matching Using Particle Filtering, *ITS Stockholm*, September 2009 [106])

Digital maps and map matching technology will continue to improve; however, current map matching algorithms seem to be performing well. Maintenance of map matching algorithms would be accomplished by the automobile manufacturer notifying the owner that a software/firmware update is necessary based on correction of any performance issues or perhaps an improvement in performance developed by the manufacturer (or his subcontractor).

The details of the associated map matching algorithms can be found in the references listed in Table 1.16-2.

Table 1.16-2. Map Matching References

[113] Bernstein, D., Kornhauser, A., 1998, *Map Matching for Personal Navigation Assistants*. Proceedings of the 77th Annual Meeting of the Transportation Research Board, 11-15 January, Washington D.C.
[114] Greenfeld, J.S., 2002, "Matching GPS Observations to Locations on a Digital Map", *Proceedings of the 81st Annual Meeting of the Transportation Research Board*, January, 2002, Washington D.C.
[80] Quddus, M., "High Integrity Map Matching Algorithms for Advanced Transport Telematic Applications", Doctoral Thesis, Imperial College of London, January 2006.
[115] Srinivasan, D., Cheu, R.L., "Development of an Improved ERP System using GPS And AI Techniques", IEEE Proceedings on Intelligent Transportation Systems, 2003.
[116] Syed, S., Cannon, M.E., 2004, "Fuzzy Logic-based Map Matching Algorithm for Vehicle Navigation System in Urban Canyons", *Proceedings of the Institute of Navigation (ION) National Technical Meeting,* 26-28 January 2004.
[117] White, C.E., Bernstein, D., Kornhauser, A.L., "Some Map Matching Algorithms for Personal Navigation Assistants", Transportation Research Part C 8, 91-108, 2000.
[118] Xu, A.G., Yang, D.K., Cao, F.X., Xiao, W.D., Law, C.L., Ling, K.V., Chua, H.C., 2002, "Prototype Design and Implementation for Urban Area In-car Navigation System", IEEE 5th International Conference on Intelligent Transportation Systems, 3 - 6 September 2002.
[119] Yang, D., Cai, B., Yuan, Y., 2003, "An Improved Map-matching Algorithm used in Vehicle Navigation System", IEEE Proceedings on Intelligent Transportation Systems, 2003.

1.17 Sensor Fusion

A key issue with ranging systems such as RADAR and LIDAR is the incidence of false positives (false alarms) and false negatives (missed detections). False positives are a result of detecting an object and incorrectly deciding that it represents a hazard. False negative are not necessarily failures to actually sense the presence of the object, but rather the failure to determine that the object represents a hazard. A typical false positive situation is illustrated in Figure 1.17-1 below. Here Vehicle A's ranging sensor will detect vehicle B, and it will decide that, since vehicle B is within a certain range and is (perhaps) stopped, that it represents a hazard (a vehicle stopped ahead). Depending on the application, the system will then either warn the driver, or apply the brakes. In reality, however, neither of these actions is warranted because the road curves and vehicle B does not actually lie on the future path of vehicle A.

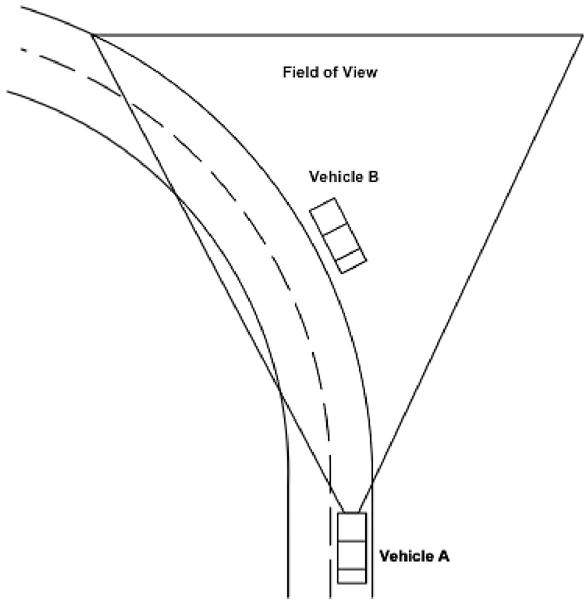


Figure 1.17-1. False Positive Caused by Parked Vehicle On-Axis
Source: ARINC April 2012

Figure 1.17-2 illustrates the same sort of scenario as figure 5.5-1 except here the stopped vehicle (vehicle B) is in the path of vehicle A, but the ranging sensor detects it as being off axis, and incorrectly assumes that it is not in the path of vehicle A. This is a missed detection, or false negative.

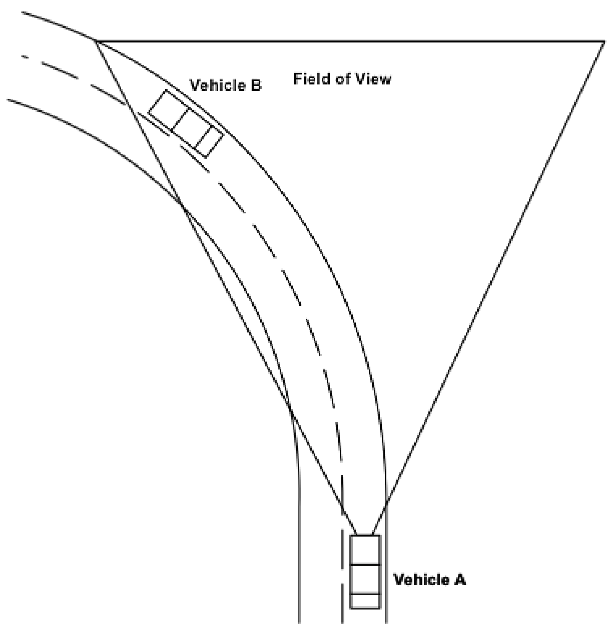


Figure 1.17-2. False Negative Cause by Stopped Vehicle Off-Axis
Source: ARINC April 2012

The simplest solution to avoid false positives of the type described in Figures 5.5-1 and 5.5-2 is to correlate the range of the detected objects with the road geometry. This would be a fusion of position sensing (for example, using GPS and a digital map with ranging. In this case the system would recognize that vehicle B in Figure 5-.5-1 is not in the path of vehicle A, and so the applications would not take action, and it would recognize that vehicle B in Figure 5.5-2 is in the path of vehicle A, and so it would take action.

Other approaches combine video data with ranging data to produce a more detailed interpretation of the scene. Higher end system may combine data from numerous sensors to develop a very sophisticated interpretation of the situation being sensed.

Figure 1.17-3 illustrates a high level system diagram related to sensor fusion as presented in research paper entitled, “Multi-sensor Data Fusion in Automotive Applications:, authored by Thomas Herpel, et al, (Reference [81]).

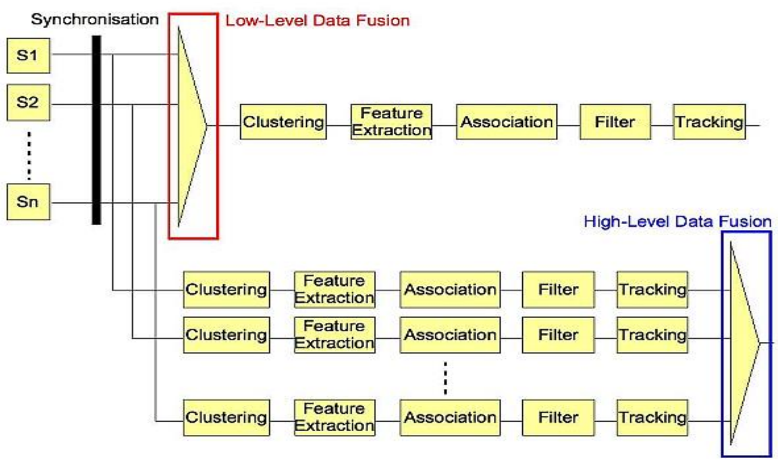


Figure 1.17-3. High Level System Diagram of Low and High Level Target Tracking and Fusion

(Ref: Herpel, T., et al, “Multi-sensor Data Fusion in Automotive Applications”, Friedrich Alexander University; Erlangen, Germany, *2008 Sensor Fusion Conference*, 2008 [81])

Figure 1.17-4 illustrates a sensor fusion diagram for integrating OBE LIDAR and Video Sensors, as discussed in the research report by Nico Kaempehen, et al, entitled, “Sensor Fusion for Multiple Automotive Active Safety and Comfort Applications” [82]**).**

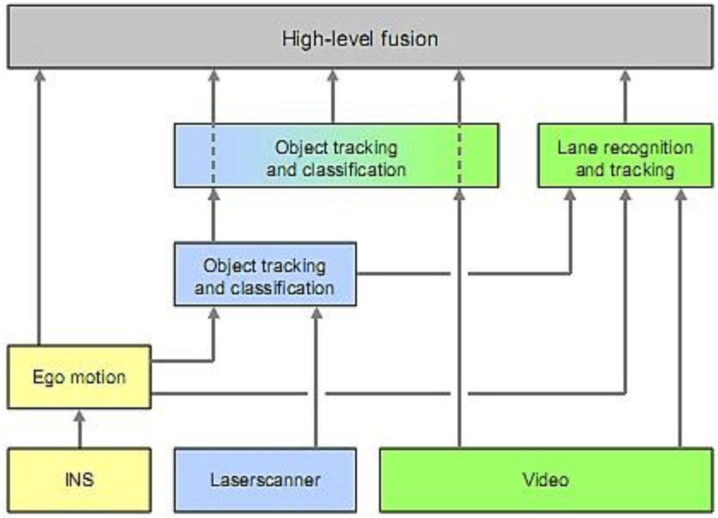


Figure 1.17-4. Sensor Fusion Architecture for LIDAR, Video, and GPS/IMU
(Ref*:* Kaempehen, N., et al, "Sensor Fusion for Multiple Automotive Active Safety and Comfort Applications"; University of Im, Germany*, Advanced Microsystems Automotive Applications 2004* [82])

Figure 1.17-5 illustrates the improved results obtained by sensor fusion as discussed in this report.

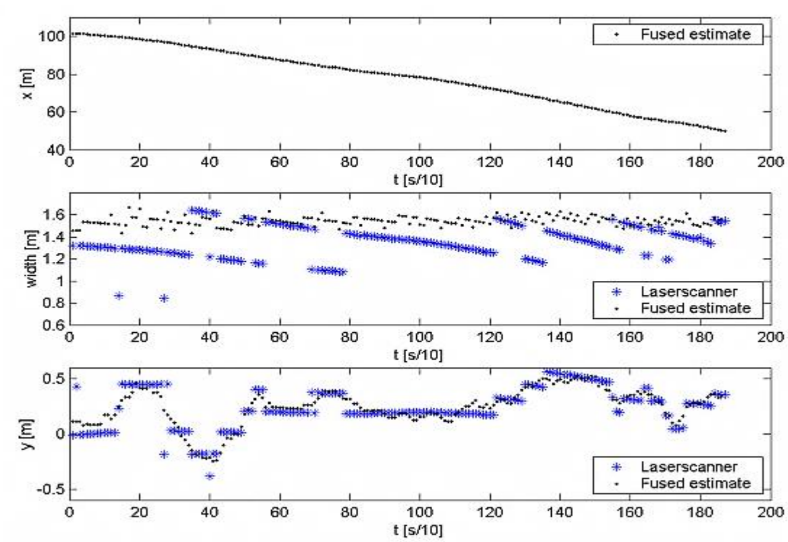


Figure 1.17-5. Results of Sensor Fusion of LIDAR and Imaging Video Illustrating Range (x), Target Width and Lateral Offset (y)
(Ref*:* Kaempehen, N., et al, "Sensor Fusion for Multiple Automotive Active Safety and Comfort Applications"; University of Im, Germany*, Advanced Microsystems Automotive Applications 2004* [82])

Figure 1.17-6 illustrates sensor tracking and fusion information flow as presented in research paper entitled, "Data Fusion in Multi-Sensor Platforms for Wide Area Perception", by Aris Polychronopoulos, et al [83]. This report indicates that processing latency is 100 msec, but could possibly be reduced to 40 msec with improved processing equipment architecture.

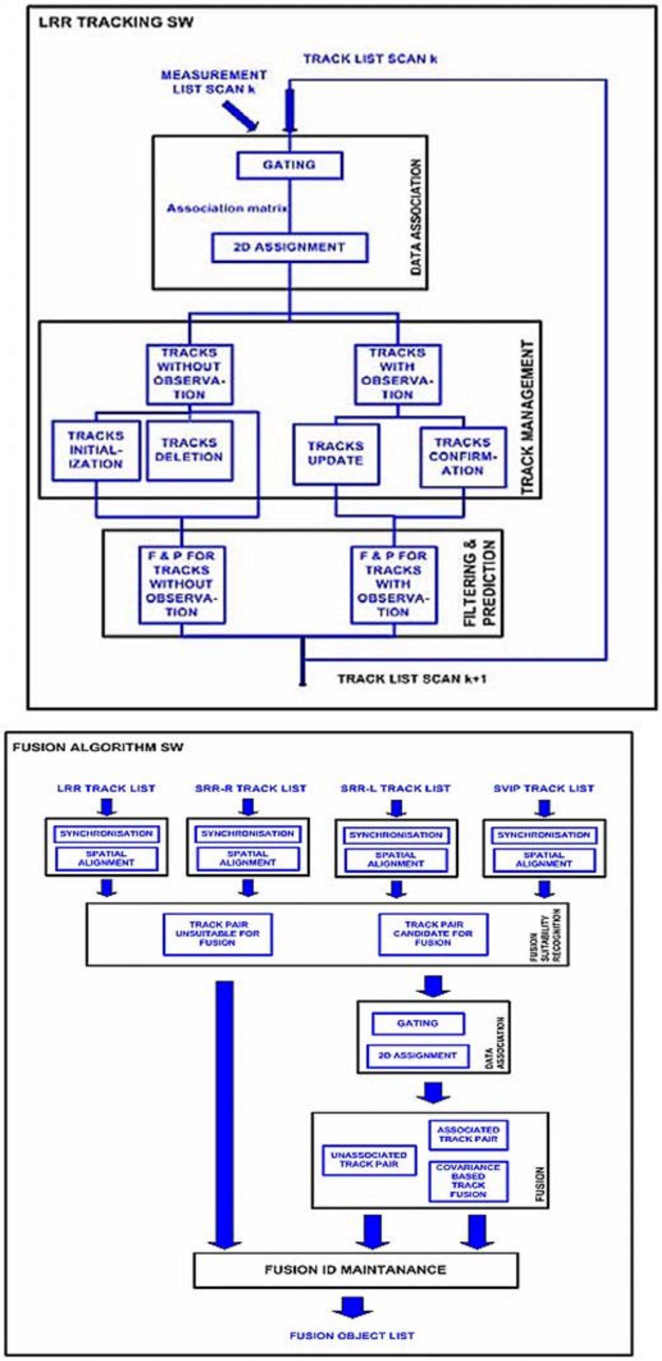


Figure 1.17-6. Example of Information Flow Related to Sensor Tracking and

Fusion

(Ref: Polychronopoulos, A., et al, "Data Fusion in Multi-Sensor Platforms for Wide Area Perception", *IEEE Intelligent Vehicles Symposium*, 2006 [83])

A technical report entitled, 'A Swedish Research Initiative on Sensor Data Fusion", authored by Malta Ahrholdt (Volvo) [84], discusses a fusion approach using features extraction from sensor data and object correlation as shown in Figure 1.17-7. This is the approach utilized by the European ProFusion initiative.

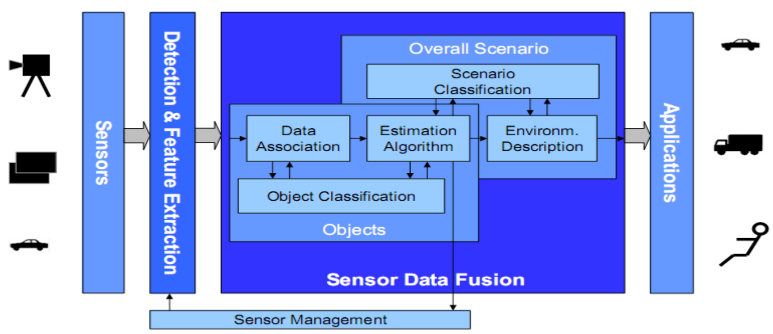


Figure 1.17-7. Sensor Data Fusion Architecture as Developed by Volvo Using Features Extraction and Object Correlation

(Ref: Ahrholdt, M. (Volvo), "A Swedish Research Initiative on Sensor Data Fusion", SEFS Program: Sensor Data Fusion for Automotive Safety Systems, Swedish IVSS Initiative on Sensor Data Fusion, October 11, 2006 [84])

Sensor data processing in vehicles will require correlation with vehicle motion sensors (IMU) to stabilize the sensor data and to remove "own vehicle" motion, allowing moving and fixed targets to be identified. Using fusion algorithms, multiple sensor data can be combined providing the best information from each sensor to refine location, motion and identity/classification of the target. For instance, RADAR range data, which is more accurate than vision based range data may be fused with image data, the RADAR information being the main contributor to target location and the image sensor providing a higher confidence identity of the target. Having multiple sensors detecting a common target further reduces false alarm rate and provides a higher confidence level related to the relative position of the target. The positioning accuracy for fused systems is equal to the accuracy for the sensor measuring each particular parameter. So, for example, if the range I measured to an accuracy of 0.1 meter using a LIDAR, and the lateral position is measured to an accuracy of 0.1 meter using video, the resulting position accuracy is 01 meter in both dimensions. Confidence is somewhat more challenging to assess. In general, the ability for one sensor to cross check the other argues for higher confidence, but the specific mathematics of this are not well defined.

Essentially sensor fusion:

- Improves the quality of the potential safety threat target report through multiple verification of measurements by multiple sensors, thus enhancing confidence; It is essential, however, that the sensors being fused are chosen such that they complement each other. It does little good, for example, to fuse data from two sensors with equivalent performance in relation to the same parameter. Generally one must identify the weaknesses in one sensor scheme and then use another sensor scheme that compensates for that weakness;
- Supports providing a total area awareness in a common grid system;
- Provides a target report with temporary loss of contact by one sensor, with a lower confidence but still with target contact;
- Supports gap filing with shorter-range sensors where necessary into a common target grid (but with lower confidence if only one sensor provides the coverage.

There are a number of challenges to multi-sensor fusion with include:

- Removing own vehicle motion form multiple sensors that perhaps operate and process data differently (this includes sensor stabilization);
- Developing a common reference system for the sensors mounted on the vehicle and considering center line and off sets;
- Converting target returns to a common grid system, considering different processing latencies and scan/target revisit rates;
- Target boundary extraction considering variations in aspect angel and azimuth resolution.
- Processing latency;
- Multiple Sensor data acquisition real time synchronization (same time measurements fused).

1.18 Target Tracking

Target trackers combine successive target returns and support the computation of velocity and acceleration vectors which are used to predict the location on the next scan cycle allowing new target return to be correlated with existing target tracks. Most tracking algorithms use some form of Kalman filter that uses a model of expected target behavior to predict the behavior (motion) of the target. Target trackers do not improve the accuracy of the sensor data, but they improve the interpretation of the data provided by the sensor. New RADAR products are available with integral target trackers.

One of the commercial off the shelf (COTS) trackers takes RADAR returns providing 0.1% of range accuracy and azimuth accuracy of 10 arc seconds and provides velocity vectors of 1 m/sec or 2% of true speed over a -55.6 to + 55.6 m/sec (-182.4 to + 182.4 ft/sec) velocity range. Velocity separation distance required is typically around 1.5 m/sec (4.92 ft/sec) to discriminate between two targets, and range separation distance typically is 1.5 to 2 meters (4.9 to 6.6 ft).

The target trackers available for vehicles track from 25 to 60 targets; infrastructure trackers can track several hundred targets.

Advertised acceleration vectors from OBE trackers support accelerations of -20 to + 20 m/s^2 (-65.6 to + 65.6 ft/s^2) with a measurement accuracy of 0.5%. Again trackers only use the sensor information provided and compute velocity and acceleration from changes in azimuth and range from scan to scan.

Target update rate will vary based on scan rate and may be 20 to 100 msec. Additional processing time is required for the target tracker to establishing a new track or update an existing track and to extinguish tracks that are no longer of interest (out of field of view for a specified period of time). Track management time is typically around 40 msec; however, it is dependent on the tracking algorithm used as well as the use of multi-core processors.

An example is provided in research report entitled, “Bayesian Occupancy Filter Based ‘Fast Clustering-Tracking’ Algorithm”, authored by Kamel Mekhnaxha, et al [49], where it is reported that the Bayesian Occupancy Filter (BOF) takes 110 msec per scan for processing. The BOF is compared with the Joint Probabilistic Data Association Filter which takes 75 msec per frame for low numbers of targets but increases to 5 seconds when the number of targets increases to 22 and clusters to 28. Thus some of the tracking algorithms provide unacceptable latencies as the number of targets and possible cluster associations increase.

The research report entitled, “A Comparison of Several Approaches to Target Tracking with Clutter”, by Lucy Pao, et al [85] compares the performance of the following tracking algorithms including:

- Nearest Neighbor (NN);
- Probabilistic Data Association Filter (PDAF);
- Mixture Reduction (MR);
- Probabilistic Multi Hypothesis Testing Filter (PMHT);
- Mean Field Event Average Maximum Likelihood Estimator (MFEAMLE).

Figure 1.18-1 provides a comparison of processing load for the different tracking approaches as indicated by the floating-point operations per second (FLOPS).

Research paper entitled, “A Comparison of Track-to-Track Fusion Algorithm for Automotive Sensor Fusion”, by Stephan Matzka, et al [50]. The technical paper indicated that execution of the asynchronous Kalman filter required 0.02 msec, cross covariance required 0.1 msec, covariance intersection required 0.13 msec and covariance union required 0.4 msec for processing. Figure 1.18-2 presents a high level overview of source of errors related to senior fusion.

Per the technical report entitled, “Improved Estimation on Target Velocity Using Multiple Model Estimates”, by Aaron Plotnik, et al [51], velocity errors of 2 cm/sec (0.07 ft/sec) and acceleration errors of 10 cm/sec^2 (4 in/sec^2) (RMSE) are typical of target trackers. There is a clear tradeoff on tracking performance and latency. A reasonable latency figure for tracking and fusion should be planned to be 50 to 100 msec. This is in addition to the scan latency associated with the sensors providing inputs to the tracker and fusion processor.

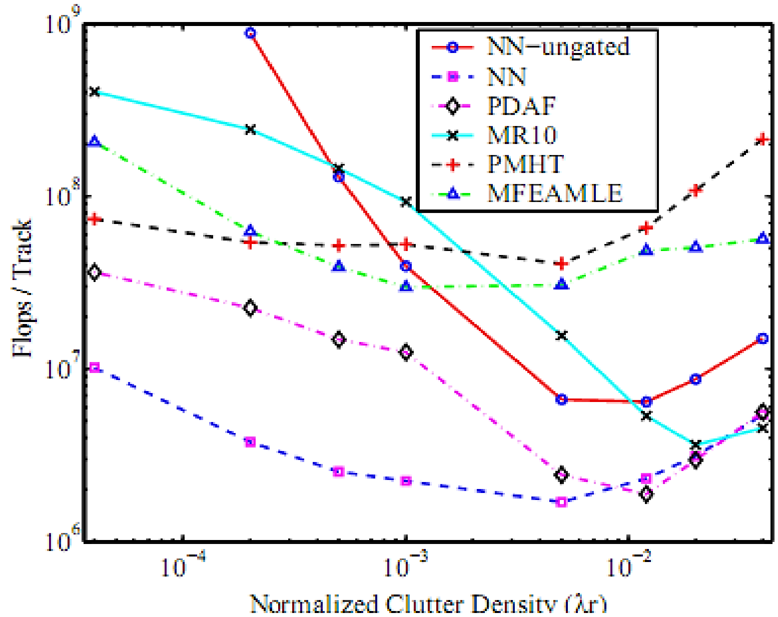


Figure 1.18-1. Comparison of Computer Processing Load Associated with Various Target Tracking Algorithms

(Ref: Pao, L., et al, "A Comparison of Several Approaches to Target Tracking with Clutter", University of Colorado at Boulder, 2003 [85])

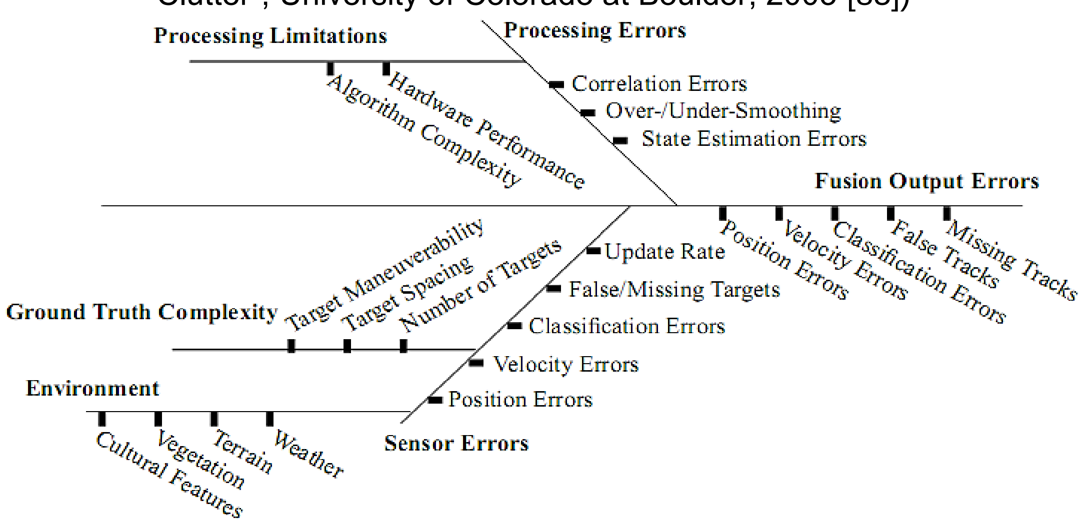


Figure 1.18-2. Source of Errors Related to Positioning and Target Tracking

(Ref: Hoffmann, M., et al, "Complexity and Performance Assessment for Data Fusion Systems", Lockheed Martin Advanced Technology Laboratories, March/April 1998 [86])

Table 1.18-1. Target Tracking References

[49]	Mekhnaxha , K., et al, "Bayesian Occupancy Filter Based Fast Clustering-Tracking" Algorithm, IEEE/RSJ International Conference on Intelligent Robots and Systems, 2008.
[50]	Matzka, S., et al, "A Comparison of Track-to-Track Fusion Algorithm for Automotive Sensor Fusion", IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems, August 2008.
[51]	Plotnik, A., et al, "Improved Estimation on Target Velocity Using Multiple Model Estimates", Stanford University, 2007.

Chapter 6 Analysis of Solutions to Application Positioning Requirements

1.19 Comparison of Positioning Systems to Application Requirements

Application positioning requirements are summarized in Table 3.1-1. In general, the driving requirement is position accuracy.

Table 1.19-1 below compares the capability of the positioning systems analyzed against the accuracy requirements for the applications. These requirements have been normalized to a 50% confidence level (which means that the position error radius will be slightly different than what is shown in Table 3.1-1), which contained requirements with various different confidence levels.

In general, the autonomous/self-contained systems that sense objects within a precise field of view, specifically RADAR and LIDAR were useful relative to all applications. The only marginal system was RADAR which typically does not have the lateral accuracy required to determine lane position, especially at long rages. In applications requiring a high degree of lateral position accuracy, RADARs were generally marginal, while LIDAR fared well. These systems also have a key advantage that they are independent, so they do not require, for example, that other vehicle to be equipped with communications or positioning capability in order to provide value to the user. This attribute is less useful, however, when the presence of the hazard is not sensible, and must be communicated, for example, with traffic signal information or MUTCD alerts and warnings. In these situations the absolute position of the vehicle must be determined, and then compared to the known (and communicated) location of the hazard. So, these systems, while excellent at providing position relative to other vehicles and measurable in-road hazards, are not useful for this other class of communicated hazard.

As expected code phase GPS also fared badly against the application requirements. Surprisingly, while this system is used extensively for low end navigation systems, the requirement derived in Section 3.3 for this application assumed that the navigation system alert the driver to an upcoming turn with sufficient time to recognize the instruction, apply the brakes and slow the vehicle to a safe speed for a residential street turn maneuver. This imposes a relatively strict position requirement that, apparently most commercial navigation systems do not meet. The high tolerance for error inherent in this application makes meeting this requirement less critical, although using any low-end navigation unit will illustrate this shortcoming.

Carrier smoothed code phase GPS systems fared much better. This system appears to be the most promising of all absolute positioning systems. It is clear that such a system must have differential corrections externally supplied (and the more timely the better). It is also unclear based on this analysis how well carrier smoothing performs in highly dynamic situations, although this could presumably be addressed with properly designed filters. The primary shortcoming for this approach appears to be the limitations of the market which favors low cost low accuracy solutions for high volume consumer applications, and high accuracy high cost instrumentation-like solutions for most industrial applications. There does not appear to be any overt reason that a higher accuracy solution cannot be produced at a relatively low cost, if the market volume warrants it.

Table 1.19-1. Summary of Application Positioning Accuracy Requirements

		Evaluated Systems								
		Code Phase GPS	Carrier Smoothed Code Phase GPS	Digital TV Ranging	Vehicle RADAR	Infrastructure RADAR	Vehicle LIDAR	Infrastructure LIDAR	UWB Transponder	Video
Application	**Position Requirement (m)**	**10-15 m Absolute**	**0.2-1.0 m Absolute**	**169 m Absolute**	**0.9 m Lateral 0.25m Long (@100 m range) Relative**	**0.3- 0.4 m Relative**	**.06 m Relative**	**.06 m Relative**	**0.24 m Absolute**	**2.0 m (@ 50 m range) 0.6 m (@ 25 m Range)**
MUTCD Related Alerts	6.7 m @ 60%	No	OK	No	No	No	No	No	OK	OK, but range is probably an issue
MUTCD Related Warnings	6.7 m @ 76.9%	No	OK	No	No	No	No	No	OK	OK, but range is probably an issue
Intersection Collision Avoidance - Traffic Signal Violation Warning	0.6 m Lateral 6.7 m Long @ 97.4%	No	OK	No	Marginal	No	No	No	OK	No
Intersection Turn-Gap Assist	1.9 m Long @ 99.7%	No	OK*	No	OK	OK	OK	OK	No	Marginal
Road Network Guidance	3.7 m Long @ 60%	Marginal	OK	No	OK	No	No	No	OK	Marginal
Lane Gate Detection and Transactions	0.6 m Lateral 1.5 m Long @ 60%	No	OK	No	No	OK	No	OK	OK	Marginal
Probe Vehicle Data Collection (Collection of Vehicle Operating Data)	1.8 m Lateral (worst case) 25 m Long @ 60%	Marginal	OK	No	No	No	No	No	OK	No
Lane Departure Warning	1.2 m lateral @ 60%	No	OK	No	No	No	No	No	No	OK
Lane Change Warning	1.2 m lateral @ 76.9%	No	OK	No	OK	No	OK	OK	No	OK
Lane Guidance	1.2 m lateral 76.9%	No	OK	No	No	No	No	No	No	OK
Automated Braking	0.3 m Lateral 2.75 m Long @ 99.7%	No	Marginal	No	OK	No	OK	No	No	Marginal
Crossing path V-V Warning	1.9 m Long @ 99.7%	No	OK	No	OK	No	OK	No	No	No

Source: ARINC April 2012

We could not identify any obvious technical requirement that would make systems like this substantially more expensive than basic GPS units, and one researcher was able to obtain very good accuracy using a basic commercial GPS receiver. The problem appears to primarily be that the GPS manufacturers do not see the market for such a receiver to be particularly attractive, so they have not developed any such systems. The only comparable performance systems are full blown survey grade equipment selling for several orders of magnitude more and including extensive other features demanded by the user community.

Ultrawideband transponder positioning systems also fared quite well. This appears to be primarily a result of the higher accuracy local pseudoranges measured by the system. As well as these systems perform, they are quite complex, and requires extensive infrastructure located at the site where the accuracy is desired. In addition, the limitations of the communications systems limit the number of vehicles that can be served, and this substantially increases latency and reduces availability.

Digital TV tower ranging was found to be totally inadequate relative to any of the applications. The methods available to improve these systems are inconsistent with the digital TV standards in the US, and are thus unlikely to ever be implemented in this country. In addition, these systems require support from the TV station operators, and there does not appear to be any reason the operators would be motivated to do anything to support this opportunistic use of their signals.

Video sensing appears to also be a promising independent position sensing means. Current video sensing systems offer relatively good performance in limited situations. However, advances in video processing, driven by the animation and gaming industry, are rapidly improving this technology. It is likely that this will become the primary independent position sensing method (over RADAR and LIDAR) during the next decade,

An unexpected observation from this study was that applications that require positioning relative to other elements (usually to other vehicles) are better served by independent relative positioning systems such as RADAR and LIDAR. While some absolute positioning systems can support the accuracy requirements, the use of an absolute positioning system for these applications implies that the hazard vehicle (the one posing the risk to the host vehicle) communicate its position to the host vehicle. If this does not occur, the host vehicle has no information. This means that the availability of position information is not only dependent on the positioning system itself, but on the probability that the other vehicle is equipped.

Appendix C provides a summary of the expected availability of these systems based on systems being manufactured as part of the annual automotive build. The fact that there are 250 M vehicles on the road today, and only about 10M to 15 M units manufactured annually means that the probability of encountering another vehicle able to communicate its position will be very low for well over a decade. This effectively reduces the availability for these positioning systems to less than 0.1% in the first five years. After 15 years it rises to 20%, and after 24 years it finally reaches 90%. In addition, for safety of life applications, an availability rate of over 95% would require that no more than 2.5% of the fleet be unequipped or inoperative at any time. Given the potential for vehicle operators to fail to maintain these systems, and lacking any regulatory means for requiring that they be tested and maintained (for example, the FAA approach to requiring aircraft certification and regular inspections), it appears unlikely that this level of availability can realistically be achieved.

References

[1] Hernandez-Pajares, M., et al, "Wide-Area RTK, High Precision Positioning on a Continental Scale", *Inside GNSS*, March/April, 2010.

[2] Takasu, T. and Yasuda, A., "Kalman-Filter-Based Integer Ambiguity Resolution Strategy for Long-Baseline RTK with Ionosphere and Troposphere Estimation", *Proceedings of the ION GNSS 2010*, September 2010.

[3] Henkel, P. and Gunther, C., "Reliable Integer Ambiguity Resolution with Multi-Frequency Code Carrier Linear Combinations", *Proceedings of the ION GNSS 2010*, September 2010.

[4] "AdVance RTK – Competitive Analysis", D14952, www.Novatel.com.

[5] Phillips, M.R., et al, "High Performance RTK for Small UAVs", *Proceedings of the ION GNSS 2010*, September 2010.

[6] Dai, L., Han, S., Wang, L., Rizos, C., "A Study on GPS/GLONASS Multiple Reference Station Techniques for Precise Real-Time Carrier Phase-Based Positioning", *Proceedings of the ION GPS 2001*, September 2001.

[7] Fotopoulos, G., Cannon, M.E., "An Overview of Multiple-Reference Station Methods for cm-Level Positioning", *GPS Solutions*, Vol. 4, No. 3, 2001.

[8] Thipparthi, S.N., "Improving Positional Accuracy Using Carrier Smoothing Techniques In Inexpensive GPS Receivers", A thesis submitted to the Graduate School in partial fulfillment of the requirements for the Degree Master of Science in Electrical Engineering, New Mexico State University, February 2004.

[9] Lee, H. K. and Rizos, C., "Performance Analysis of Position-Domain Hatch Filter", Published by SNAP, University of New South Wales, http://www.gmat.unsw.edu.au/snap/publications/leehy_etal2003d.pdf

[10] Booth, J. and Lunde, T., "Carrier-Phase DGPS System Accuracy Tests: Increasing Baseline Distance and Using CORS Network Data", *Proceedings of the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation* (ION GPS/GNSS 2003), September 9 - 12, 2003.

[11] "The CSmooth Command – Preliminary; White Paper from Novatel, November 15, 1997, White Paper ANP_014 Rev 1, http://webone.novatel.ca/assets/Documents/Bulletins/apn014.pdf.

[12] Pruitt, G. and Fly, C.E., "NDGPS Assessment Report", ARINC Incorporated, prepared under FHWA contract No. DTFH61-04-D-00002, March 2008.

[13] Schwartz, Dr. D., "Delphi Sensor Fusion for Automotive Safety", Delphi*, PReVENT/ProFusion2 Fusion Forum Workshop*, March 2006.

[14] MacGougan, G., "Real-time Kinematic Surveying using Tightly Coupled GPS and UWB Ranging", UCGE 20293, August 2009, University of Calgary, Schulich School of Engineering, August 2009.

[15] Federal Communications Commission, "Revision of Part 15 of Commissions' Rules Regarding Ultra Wideband", April 22, 2001.

[16] Carlin, J., et al,” Evaluation of Cost Effective Sensor Combinations for a Vehicle Pre-Crash Detection System”,Cal Poly San Luis Obispo, *Proceedings of the 2005 Commercial Vehicle Engineering Congress and Exhibition*, November 2005.
[17] Strobel, T., “State-of-the-art of Sensors and Sensor Data Fusion for Automotive Preventive Safety Applications”, PR-13400-IPD-040531-v10, University of Passau, July 19, 2004.
[18] USDOT Highway Financial Data and Information, Our Nation's Highways: 2010.
[19] Sole, A., et al, “Solid or Not Solid: Vision for RADAR Target Validation”, MobileEye™ Vision Technologies Ltd.,2004, http://www.mobileye.com/wpcontent/uploads/2011/09/SolidOrNotSolid.pdf.
[20] Porikli, F., et al, "Integrated Detection, Tracking and Recognition for IR Video Based Vehicle Classification", Mitsubishi Electric Research Labs, TR2007-04, 2007.
[21] Premebida, C., “A LIDAR and Vision Approach for Pedestrian and Vehicle Detection and Tracking”, *IEEE Intelligent Transportation Systems Conference, 2007*, September 30, 2007.
[22] Keller, C. G., et al, “Dense Stereo-Based ROI Generation for Pedestrian Detection”, University of Heidelberg, *Proceedings of the 31st DAGM Symposium on Pattern Recognition*, 2009.
[23] Rranke, U., “From Door-to-Door: Principles and Applications of Computer Vision in Driver Assisted Systems”, DaimlerChrysler AG, October 4, 2001.
[24] Betke, M., et al, “Multiple Vehicle Detection and Tracking in Hard Real Time”, University of Maryland, Institute for Advanced Computer Studies, presented at *IEEE Intelligent Vehicles Symposium*, 1996.
[25] Haanpaa, D., “Automatic Target Classifier Using Model Based Image Processing”, *35th Applied Imagery and Pattern Recognition Workshop* (AIPR'06), October 2006.
[26] Brown, A., (NAVSYS Corp.), “Precise Position and Attitude Geo-registration of Video Imagery for Target Geolocation”, *24th JSDE Symposium*, Anaheim, CA, 1998.
[27] Liang, Yu-Ming, et al; “Video Stabilization for a Camcorder Mounted on a Vehicle*”, IEEE Transactions on Vehicle Technology*, Volume 53, Number 6, Volume 53, Number 6, November 2004.
[28] Seko, Yasuji, et al (FujiXerox), “3D Position Measurement Technology”,*SPPRA '08 Proceedings of the Fifth IASTED International Conference on Signal Processing, Pattern Recognition and Applications,* 2008.
[29] Minge, E., et al, “Evaluation of Non-Intrusive Technologies for Traffic Detection”, MNDOT Report MN/RC 2010-36, September 2010.
[30] Middleton, D. (PhD), et al, “Advances in Traffic Data Collection”, Texas Transportation Institute; January 31, 2003.
[31] Zong, T., et al, “Vehicle Tracking and Speed Measurement at Intersections Using Video Detection Systems”, *ITE Journal*, January 2009.

[32] Gupte, S., et al, "Detection and Classification of Vehicles", *IEEE Transactions on Intelligent Transportation Systems*, Volume 3, No. 1, March 2002.
[33] Malinovsky, Y., "Model-Free Video Detection and Tracking of Pedestrians and Bicyclist", Computer-Aided Civil and Infrastructure Engineering, Volume 24, 2009.
[34] Kanhere, N., "Vision-Based Detection, Tracking and Classification of Vehicles using Stable Features with Automatic Camera Calibration", PhD thesis at Clemson University, August 2008.
[35] "What Kinect Sees", http://www.youtube.com/watch?v=pk_cQVjqFZ4&feature=related By: Code Laboratories/NUI.
[36] Tech Report: "Kinect - The Latency Question", http://imagequalitymatters.blogspot.com/2010/08/tech-report-kinect-latency-question.html.
[37] Wang, J., "Intelligent MEMS INS/GPS Integration for Land Vehicle Navigation", PhD thesis at University of Calgary, September 2006.
[38] Pratt, K., et al, "Sensor Fusion for Robot Navigation using a Fuzzy-EKF with Weighted Covariance", University of South Florida.
[39] Hasan, A., et al (University of Malaysia), "Integration of GPS and INS with Differential Sampling Rate using Adaptive Neuro Fuzzy Interference System", *World Applied Science Journal* ,Volume 7, 2009.
[40] Toledo-More, R., et al, "High-Integrity IMN-EKF-Based Road Vehicle Navigation with Low-Cost GPS/SBAS/INS", *IEEE Transactions on ITS*, Volume 8, Number 3, September 2007.
[41] "Safety Digital Maps Requirements", PReVENT Report PR-12310-SPD-040607-V10-TEL, September 2004.
[42] "NHTSA Enhanced Digital Mapping Project (EDMap) Final Report", November 2004.
[43] Trach, W. Jr, et al, "Final Report - Driver Assistive System for Rural Applications", MnDOT, Report MN/RC-2005-30, August 2005.
[44] Schroedl, S. (Daimler Chrysler), "Mining GPS Traces for Map Refinement", *Data Mining and Knowledge Discovery 9*, pp. 59–87, 2004.
[45] Greenfield, J. (PhD, "Digital Map Requirements for AVL", The National Center for Transportation and Industrial Productivity; New Jersey Institute of Technology, December 1998.
[46] Rogers, S., et al, "Creating and Evaluating Highly Accurate Maps with Probe Vehicles", *IEEE Conference on Intelligent Transportation Systems*, 2000.
[47] Cheng, P., "Evaluation of Digital Maps for Road User Charging Applications", University of Minnesota, August 2004.
[48] Society of Automotive Engineers, "SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary", 2009.
[49] Mekhnaxha , K., et al, "Bayesian Occupancy Filter Based Fast Clustering-Tracking" Algorithm, IEEE/RSJ International Conference on Intelligent Robots and Systems, 2008.

[50] Matzka, S., et al, “A Comparison of Track-to-Track Fusion Algorithm for Automotive Sensor Fusion”, *IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems,* August 2008.
[51] Plotnik, A., et al, “Improved Estimation on Target Velocity Using Multiple Model Estimates”, Stanford University, 2007.
[52] “Discussion Paper No. 8, A Stopping Sight Distance and Decision Sight Distance”, prepared for Oregon Department of Transportation, Salem, Oregon, by the Kiewit Center for Infrastructure and Transportation, Oregon State University Corvallis, Oregon September 2004.
[53] Salim, F., “A Context-Aware Framework for Intersection Collision Avoidance”, PhD Thesis at Monash University, Australia, August. 2008.
[54] www.microwaves101.com/encyclopedia.
[55] Joeng, S., et al, “Design of a 24 GHz RADAR with Subspace-Based Digital Beam Forming for ACC Stop-and-Go System”, *ETRI Journal*, Volume 32, Number 5, October 2010.
[56] Federal Communications Commission, Office of Engineering and Technology, Bulletin #70, Millimeter Wave Propagation, July, 1997.
[57] Szewczyk , R., “UWB: Technology and Implications for Sensor Networks”, *NEST Conference,* August 27, 2004.
[58] Chiu, D., “Ultra Wideband Augmentation of GPS”, University of Calgary, UCEG Thesis 20277, December 2008.
[59] Vydhyanathan, A., et al, “Augmenting Low-cost GPS/INS with UWB Transceiver for Multi-platform Relative Navigation”, *Proceedings of the 22nd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS) 2009*.
[60] O’Keefe, K., et al, “Demonstration of Inter-vehicle UWB Ranging to Augment DGPS for Improved Relative Positioning”, *ION GNSS 2010*, September 2010.
[61] Schoitsch. E., “Reliable Application Specific Detection of Road Users with Vehicle On-board Sensors”, ADOSE Report FD7-ICT-2007-1, 2007.
[62] Advanced Scientific Concepts, Inc., Technical Product Literature, 2010.
[63] Velodyne Inc., Technical Product Literature, 2010.
[64] Takashi Ogawa & Kiyokazu Takagi (Denso, Corp.), “Lane Recognition Using On-vehicle LIDAR”, *Proceedings of the Intelligent Vehicles Symposium 2006*, June 13-15, 2006, Tokyo, Japan.
[65] USDOT FHWA, “Traffic Detector Handbook”, FHWA-HRT-06-108, October 2006.
[66] Cheng, H., et al, “Development and Field Test of a Laser-Based Nonintrusive Detection System for Identification of Vehicles on the Highway, *IEEE Transactions on ITS*, Volume 6, Number 2, June, 2005.
[67] Jazayeri, A., et al, ”Vehicle Detection and Tracking in Car Video Based on Motion Model”, Purdue University, *IEEE Transactions on Intelligent Transportation Systems*, Volume 12, Issue 2, June 2011.
[68] Pflugfelder, R., “Self Calibrating Cameras in Video Surveillance”, PhD Thesis, Graz University, Australia, May 2008; and Liang, Yu-Ming, et al, “Video

Stabilization for a Camcorder Mounted on a Vehicle*", IEEE Transactions on Vehicular Technology*, Volume 53, Number 6, November 2004.
[69] Llorca, D.,et al, "Vision Based Traffic Data Collection Sensor for Automotive Applications", *Sensors*, Volume 10, Number 1, January, 2010.
[70] US Patent Application 2010/0199228, August 5, 2010.
[71] Code Laboratories, http://www.youtube.com/watch?v=pk_cQVjqFZ4&feature=related.
[72] "Reference Execution Platform", CVIS Project Document D.CVIS.4.1, June 30, 2009.
[73] Major IMU Manufacturer's Installation Manual.
[74] Gautier, J., "GPS/INS Generalized Evaluation Tools for Design and Testing of Integrated Navigation Systems", PhD Thesis, Stanford University, June 2003.
[75] Wan, E., et al (Ohio State University), "Sigma-Point Kalman Filter Based Integrated Navigation System", *Proceedings of the 60th Annual Meeting of The Institute of Navigation*; June 7 - 9, 2004.
[76] eSafety Forum, Digital Map Working Group, "Final Report – Recommendations", November 28, 2005.
[77] Maile, M., "V2V and V2I Communications Based Safety Applications", SAE presentation, 2010.
[78] Cheng, P. (University of Minnesota), "Evaluation of Digital Maps for Road User Charging", MNDOT Report Mn/RC 2003-38, 2003.
[79] Loannis , K. (University of Crete), "A Map Matching Algorithm for Car Navigation Systems with GPS Input", *10th AGILE International Conference on Geographic Information Science 2007*, Aalborg University, Denmark.
[80] Quddus, M., "High Integrity Map Matching Algorithms for Advanced Transport Telematic Applications", Doctoral Thesis, Imperial College of London, January 2006.
[81] Herpel, T., et al, "Multi-sensor Data Fusion in Automotive Applications", Friedrich Alexander University; Erlangen, Germany, *2008 Sensor Fusion Conference*, http://www7.informatik.uni-erlangen.de/~herpel/publications/pdf/herpel2008sensorfusion.pdf, 2008.
[82] Kaempehen, N., et al, "Sensor Fusion for Multiple Automotive Active Safety and Comfort Applications"; University of lm, Germany, *Advanced Microsystems Automotive Applications 2004*.
[83] Polychronopoulos, A., et al, "Data Fusion in Multi-Sensor Platforms for Wide Area Perception", *IEEE Intelligent Vehicles Symposium*, 2006.
[84] Ahrholdt, M. (Volvo), "A Swedish Research Initiative on Sensor Data Fusion", SEFS Program: Sensor Data Fusion for Automotive Safety Systems, Swedish IVSS Initiative on Sensor Data Fusion, October 11, 2006.
[85] Pao, L., et al, "A Comparison of Several Approaches to Target Tracking with Clutter", University of Colorado at Boulder, 2003.
[86] Hoffmann, M., et al, "Complexity and Performance Assessment for Data Fusion Systems", Lockheed Martin Advanced Technology Laboratories, March/April 1998.

[87] Federal Highway Administration, “Final Report: Vehicle Infrastructure Integration: Proof of Concept Technical Description - Vehicle”; FHWA-JPO-09-017, May 19, 2009.
[88] Schulze, M. et al, “PReVENT, a European Program to Improve Active Safety”; DaimlerChrysler AG, Stuttgart, Germany, June 27, 2005.
[89] Southworth, M., “EFV Keeps Pace with Ethernet to Actualize Net-centric Warfare”, *Military Embedded Systems*, August 14, 2009.
[90] CVIS Project Information, www.cvisproject.org.
[91] Middleton, D., et al, “Alternative Vehicle Detection Technology for Traffic Signal Systems”, TAMU Report 0-5845-1, February 2009.
[92] Mehr, W., “Advanced Driver Assist Products for Commercial Vehicles”, Continental AG, June 25, 2009.
[93] COPAR Inc. RADAR Technical Product Data.
[94] Schneider. M., “Automotive RADAR – Status and Trends”, Robert Bosch GmbH, Corporate Research, Hildesheim, Germany, 2005, http://duepublico.uni-duisburg-essen.de/servlets/DerivateServlet/Derivate-14581/Paper/5_3.pdf.
[95] Federal Highway Administration, Document FHWA-HRT-06-108; “Traffic Detector Handbook”, October 2006.
[96] Salim, F., “A Context-Aware Framework for Intersection Collision Avoidance”, PhD Thesis, Monash University, Australia, August 2008.
[97] “Radar Cross Section”, www.microwaves101.com/encyclopedia, 2010.
[98] Joeng, S., et al, ”Design of a 24 GHz RADAR with Subspace-Based Digital Beam Forming for ACC Stop-and-Go System”, *ETRI Journal*, Volume 32, Number 5, October 2010.
[99] “Continuous-wave radar”, Wikipedia, http://en.wikipedia.org/wiki/Fm-cw_radar#Modulated_continuous-wave, 2011.
[100] MacGougan, G., et al, “UWB Ranging Precision and Accuracy”, *Measurement Sciences and Technology*, Volume 20, Number 9, 2009.
[101] Federal Communications Commission, FCC Document 02-48, “Revision of Part 15 of Commissions’ Rules Regarding Ultra Wideband”, April 22, 2002.
[102] American National Standards Institute, “Laser Safety Standards”,Standard ANSI Z136, 2007.
[103] Chang, J. (Noblis), “Market Penetration Analysis for VSC-A Safety Benefit Opportunities Estimation”, Prepared under FHWA Contract #: DTFH61-05-D-00002, June 8, 2010.
[104] USDOC, NTIA Document, "Communications Receiver Performance Handbook", JSC-CR-06-072, 2006.
[105] Broadspec UWB Antenna, Time Domain Corp. Technical Data, 2010.
[106] Bonnifait, et al, “Multi-Hypothesis Map Matching Using Particle Filtering, *ITS Stockholm*, September 2009.
[107] www.Radartutorial.edu, 2011.
[108] Jan, A., et al, “A Fully Integrated 24 GHz Phased Array Transmitter in CMOS”, *IEEE Journal of Solid State Circuits*, Volume 40, Number 12, 2005.

[109] Skog, I., Handel, P., "Calibration of a MEMS Inertial Measurement Unit", *Metrology for a Sustainable Development*, September, 17–22, 2006 Rio de Janeiro, Brazil.

[110] Aggarwal, P., et al, "Cost-effective Testing and Calibration of Low Cost MEMS Sensors for Integrated Positioning, Navigation and Mapping Systems", *Shaping the Change XXIII FIG Congress*, Munich, Germany, October 8-13, 2006.

[111] Dorata, A.,et al, "Driving the Line", *GPS World*, March 2003.

[112] Kuga, H.K., et al, "Experimental Static Calibration of an IMU Based on MEMS", *Proceedings of the 19th International Congress of Mechanical Engineering*, November 5-9, 2007.

[113] Bernstein, D., Kornhauser, A., 1998, "Map Matching for Personal Navigation Assistants", *Proceedings of the 77th Annual Meeting of the Transportation Research Board*, 11-15 January, Washington D.C.

[114] Greenfeld, J.S., 2002, "Matching GPS Observations to Locations on a Digital Map", Proceedings of the 81st Annual Meeting of the Transportation Research Board, January, 2002, Washington D.C.

[115] Srinivasan, D., Cheu, R.L., "Development of an Improved ERP System using GPS And AI Techniques", *IEEE Proceedings on Intelligent Transportation Systems*, 2003.

[116] Syed, S., Cannon, M.E., 2004, "Fuzzy Logic-based Map Matching Algorithm for Vehicle Navigation System in Urban Canyons", *Proceedings of the Institute of Navigation (ION) National Technical Meeting*, 26-28 January 2004 .

[117] White, C.E., Bernstein, D., Kornhauser, A.L., "Some Map Matching Algorithms for Personal Navigation Assistants", Transportation Research Part C 8, 91-108, 2000.

[118] Xu, A.G., Yang, D.K., Cao, F.X., Xiao, W.D., Law, C.L., Ling, K.V., Chua, H.C., 2002, "Prototype Design and Implementation for Urban Area In-car Navigation System", *IEEE 5th International Conference on Intelligent Transportation Systems*, 3 - 6 September 2002.

[119] Yang, D., Cai, B., Yuan, Y., 2003, "An Improved Map-matching Algorithm used in Vehicle Navigation System", *IEEE Proceedings on Intelligent Transportation Systems*, 2003.

[120] Bird, C., "New Safety Techniques Takes Decades to Hit the Entire Market by Colin Bird", In the News: Safety, Cars.com, January 25, 2012.

[121] "As Electronics Expand, So Do Challenges Facing Automobile Designers", *Automotive News*, September 29, 2010.

[122] Broy, M., "Challenges in Automotive Software Engineering*", Proceedings of the 28th International Conference on Software Engineering*, 2006.

[123] Christiansen, L., et al, "Investigating the Effects of an Advanced Warning In-Vehicle System on Behavior and Attention in Controlled Driving", *Proceedings of the 3rd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2011.

[124] Do, J., et al, "Multi-Fault Tolerant RAIM Algorithm for Hybrid GPS/TV Positioning", Stanford University.

[125] Strus, J., et al., "Development of a High Accuracy Positioning System for Platform Maneuvering", *Inside GNSS*, Mar/Apr 2008.
[126] Sun, D., et al, "GPS/Reduced IMU with a Local Terrain Predictor in Land Vehicle Navigation", *International Journal of Navigation and Observation*, Volume 2008, 2008.
[127] Bevy, D., et al, "Parametric Error Equations for Dead Reckoning Navigation in Ground Vehicle Guidance and Control", *Navigation*, Volume 53, 2007.
[128] Sanoli, S., Conte, G., "Developing an Inertial Navigation System for Guidance and Control of Underwater Vehicles".
[129] Wang, J., et al, "Improving Adaptive Kalman Filter in GPS/SDINS Integration with Neural Network".
[130] McNamara, D., "Human Machine Interface Report", (www.telematicsupdate.com/human-machine-interface-report/index2.php, 2012.

Peyet, F., et al, "Lane-level Positioning for Cooperative Systems Using EGNOS and Enhanced Digital Maps", Laboratoire Central des Ponts et Chaussees, Bouguenais, FR, *15th World Congress on ITS*, 16-20 November 2008.

Appendix A - List of Acronyms

2D	Two Dimensional
3D	Three Dimensional
A	
AASHTO	American Association of State Highway and Transportation Officials
AC	Alternating Current
ACAS	Automated Collision Avoidance System
ACC	Adaptive Cruise Control
ACN	Automatic Collision Notification
ACS	Attitude Control System
ADAS	Advanced Driver Assist System
AFI	Automatic Fault Indication
AFLT	Advanced Forward Link Trilateration
AGPS	Assisted Global Positioning System
AHS	Automated Highway System or Advanced Highway System
AIB	Autonomous Integrity Beacon
AM	Amplitude Modulation
ANSI	American National Standards Institute
ANT	Antenna
AOA	Angle of Arrival
AP	Access Point
API	Application Program Interface
APTA	American Public Transit Association
APTS	Advanced Public Transportation Systems
ARW	Angular Rate Random Walk
ASC	Actuated Signal Controller
ATA	American Trucking Association

ATC	Advanced Transportation Controller
ATIS	Advanced Traveler Information System
ATMS	Advanced Traffic Management System
ATP	Acquisition, Tracking & Pointing
ATS	Automatic Test System
AVC	Automated Vehicle Classification
AVCS	Advanced Vehicle Control Systems
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
AVLS	Automatic Vehicle Location System
AVM	Automatic Vehicle Monitoring
AWS	Advisory Warning System
Az	Azimuth
B	
BER	Bit Error Rate
BIT	Built in Test
bps	Bits per Second
BPP	Bits per Pixel
BS	Base Station
BTH	Beyond the Horizon
BW	Bandwidth
BWC	Bandwidth Compression
C	
C/A-code	Coarse/Acquisition Code
CAN	Controller Area Network
CCA	Circuit Card Assembly
CCD	Charge Coupled Device
CDGPS	Carrier Phase Differential GPS
CEP	Circular Error Probability

CM	Configuration Management
CSMA/CD	Carrier Sense Multiple Access / Collision Detection
CTP	Critical Technical Parameter
CW	Continuous Wave
D	
DAB	Digital Audio Broadcasting
DARPA	Defense Advanced Research Projects Agency
dB	Decibel
dBm	Decibel relative to one milliWatt
dBW	Decibel relative to one Watt
DBMS	Data Base Management System
DC	Direct Current
DD	Differential Doppler
DF	Direction Finding
DGPS	Differential GPS
DGS	Deployable Ground Stations
DIPS	Digital Image Processing System
DOA	Direction of Arrival
DoD	Department of Defense
DOP	Dilution of Precision
DMS	Digital Mapping System
DPCM	Differential Pulse Code Modulation
DR	Dead Reckoning
DSRC	Dedicated Short Range Communications
DSS	Decision Support System
DSSS	Driving Safety Support System
DWT	Discrete Wavelet transform
E	
E-911	Enhanced 911

E-OTD	Enhanced Observed Time Difference
ECEF	Earth Centered Earth Fixed
EF	Earth Fixed
EFLT	Enhanced Forward Link Trilateration
EIA	Electronics Industry Alliance
EIS	Enhanced Imaging System
EKF	Extended Kalman Filter
El	Elevation
EM	Electromagnetic
EMC	Emergency Management Center
EMI	Electromagnetic Interference
EMS	Emergency Medical Services
EO	Electro-Optical
EOC	Emergency Operations Center
EO/IR	Electro-Optical/Infrared
E-OTD	Enhanced Observed Time Difference
ERP	Effective Radiated Power
ERTICO	European Road Transport Telematics Implementation Coordination Organization
ESS	Environmental Sensor Station or Environmental Sensor System
ETC	Electronic Toll Collection
ETTM	Electronic Toll and Traffic Management
F	
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FCW	Front Collision Warning
FDE	Fault Detection and Exclusion
FDMA	Frequency Division Multiple Access
FDP	Fusion Data Processor

FFT	Fast Fourier Transform
FHWA	Federal Highway Administration (of USDOT)
FL	Focal Length
FLIR	Forward-Looking Infrared
FM	Frequency Modulated
FMCSA	Federal Motor Carrier Safety Administration
FMCW	Frequency Modulated Continuous Wave
FMOP	Frequency Modulation On Pulse
FO	Fiber Optic
FOG	Fiber Optic Gyro
FOV	Field of View
FREQ.	Frequency
ft	Feet (‘)
FSK	Frequency Shift Keying
FTA	Federal Transit Administration (of USDOT)
G	
G	Giga ($1x10^9$)
GB	Giga Byte
GDF	Geographic Data File
GDOP	Geometric Dilution of Precision
GHz	Giga Hertz
GIS	Geographic information system
GLONASS	Global Orbiting Navigation Satellite System
GMT	GMT
GN&C	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Gyro	Gyroscope
H	

HAR	Highway Advisory Radio
HAZMAT	Hazardous Materials
HDOP	Horizontal Dilution of Precision
HF	High Frequency
HHI	Highway-Highway Intersection
HMI	Human Machine Interface
HOV	High Occupancy Vehicle
HR	High Resolution
HRI	Highway-Rail Intersection
HRR	High Resolution RADAR
HS	High Sensitivity
HSGPS	High Sensitivity GPS
HSR	High Speed Rail
HUD	Heads-Up display
HW	Hardware
Hz	Hertz
I	
IBLS	Integrity Beacon Landing System
IC	Integrated Circuit
ICC	Intelligent Cruise Control
IDB	ITS Data Bus
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IIR	Imaging Infrared
ILS	Instrument Landing System
IMES	Indoor Messaging System
IMU	Inertial Measurement Unit
In.	Inches (“)
INS	Inertial Navigation System

I/O	Input - Output
ION	Institute of Navigation
IP	Internet Protocol
IPLL	INS Doppler Aided Phase Locked Loop
IPP	Impact Point Prediction
IR	Infrared
IRAA	Infrared Acquisition Array
IRSS	IRSS
IRST	Infrared Search and Track
ISA	Inertial Sensor Assembly
ISO	International Organization for Standardization
ISP	Information Service Provider
ISS	Integrated Sensor System
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation Systems
ITU	International Telecommunications Union
IVIS	In-Vehicle Information System
J	
JAXA	Japan Aerospace Exploration Agency
JPEG	Joint Photographic Expert Group
JPL	Jet Propulsion Laboratory
JPO	Joint Program Office (of FHWA)
JS	Joint Standards
K	
k	Kilo ($1x10^3$)
Ka	Ka Frequency Band
kbps	Kilobits Per Second
KF	Kalman Filtering
Kg	Kilogram

kHz	Kilo Hertz (Hertz X 1,000)
km	Kilometer
Ku	Ku Frequency Band
KW	Kilo Watt
L	
L1	GPS primary frequency, 1575.42 MHz
L2	GPS secondary frequency, 1227.6 MHz
L3	GPS frequency, 1381.05 MHz
LAAS	Local Area Augmentation System
LAN	Local Area Network
LASER	Light Amplification by Stimulated Emission of Radiation
Lbs	Pounds
LBS	Location-Based Services
LCA	Lane Change Assist
LCC	Life Cycle Cost
LDW	Lane Departure Warning
LED	Light Emitting Diode
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
LKF	Linearized Kalman Filter
LKS	Lane Keep Support
LL	Local Level
LLA	Latitude, Longitude and Altitude
LLLTV	Low Light Level Television
LMS	Location and Monitoring Service
LOFT	LOFT
LOS	Line of Sight
LPD	Low Probability of Detection
LR	Long Range

LRMS	Location Reference Message Specification
LRR	Long Range RADAR
LRU	Line Replaceable Unit
LSE	Least-Squares Estimate
LTA	Left Turn Assist
LWIR	Long Wavelength Infrared
M	
M	Mega ($1x10^6$)
m	Meters
Max	Maximum
Mbps	Megabits per second
MCD	Minimum Cost Design
MCMIS	Motor Carrier Management Information System
MEMS	Micro-Electro-Mechanical-Systems
MEO	Medium Earth Orbit
MHz	Megahertz (Hertz X 1,000,000)
MIB	Management Information Base
mm	Millimeter
MMI	Man Machine Interface (Same as HMI)
MIMIC	Microwave/Millimeter Wave Monolithic Integrated Circuit
MMW	Millimeter Wave
MOE	Measure of Effectiveness
MOP	Measure of Performance
MPEG	Motion Pictures Expert Group
MPO	Metropolitan Planning Organization
MR	Medium Range
MRR	Medium Range RADAR
MS	Mobile Station
MSI	Multispectral Imager

MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
MUTCD	Manual on Uniform Traffic Control Devices
MW	Megawatt
MW	Microwave
mW	milliWatt
MWIR	Medium Wave-length Infrared
N	
N/A	Not Available or Not Applicable
NEMA	Association of Electrical and Medical Imaging Equipment Manufacturers (NEMA), formerly known as National Electrical Manufacturers Association
NENA	National Emergency Number Association
NHI	National Highway Institute
NHTSA	National Highway Traffic Safety Administration (of USDOT)
NIST	National Institute of Standards and Technology
NRC	National Research Council
NRT	Near-Real-Time
nsec	nanoseconds
NSF	National Science Foundation
NTCIP	National Transportation Communications for ITS Protocol
NTIA	National Telecommunications and Information Administration
NTP	Network Time Protocol
NTSB	National Transportation Safety Board
O	
OBE	On Board Equipment (equipment in a vehicle)
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency division Multiplexing
OS	Operating System

OSI	Open Systems Interconnection
OTODA	Observed Time Difference of Arrival
OTDOA-IPDL	Observed Time Difference of Arrival with network adjusted Idle Period Downlink
P	
P code	Precise Code
PCB	Printed Circuit board
PCS	Personal Communications Services
PD	Pulse Doppler (RADAR)
PDOP	Position Dilution of Precision
PDR	Pedestrian Dead Reckoning
PLL	Phase Lock Loop
PMPP	Point-to-Multipoint Protocol
POA	Point of Association
ppm	Parts-Per-Million
PPP	Point-to-Point protocol
PPS	Precision Positioning Service
PRC	People's Republic of China
PRF	Pulse Repetition Frequency
PRN	Pseudo Random Number
PRN	Pseudo Random Noise
PSAP	Public Safety Answering Point
PSD	Power Spectrum Density
psec	Picoseconds
PSK	Phase Shift Keying
PVT	Position, Velocity, and Time
PW	Pulse Width
Q	
QA	Quality Assurance
QC	Quality Control

R	
RADAR	Radio Detection And Ranging
RAIM	Receiver Autonomous Integrity Monitoring
RAM	RADAR Absorbing Material
RBDS	Radio Broadcast Data System
Rcvr.	Receiver
RCS	RADAR Cross Section
R&D	Research and Development
RDS	Radio Data System
RF	Radio Frequency
RFI	Radio Frequency Interference
RFID	Radio Frequency Identification
RLG	Ring Laser Gyroscope
RM	Reliability and Maintainability
RM&A	Reliability, Maintainability, and Availability
RM&S	Reliability Maintainability, and Supportability
RMS	Root Mean Square
RSE	Roadside Equipment
RSS	Root Sum Square
R/T	Receiver/Transmitter
RTA	Right Turn Assist
RTD	Round Trip Delay
RWIS	Road Weather Information System
Rx	Receive
S	
SAE	Society of Automotive Engineers
SDO	Standards Development Organization
SEP	Spherical Probability of Error
SNMP	Simple Network Management Protocol

SNR	Signal to Noise Ratio
SR	Short Range
SRA	Shop Replaceable Assembly
SRR	Short Range RADAR
SRU	Shop Replaceable Unit
STD	Standard Deviation
STMP	Simple Transportation Management Protocol
SWIR	Short Wave Infrared
T	
TA	Time Advance
TCIP	Transit Communication Interface Protocol
TCP	Transmission Control Protocol
TCT	Time Critical Targets
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TDOA	Time Difference of Arrival
TDOP	Time Dilution of Precision
TIA	Telecommunications Industry Association
TLE	Target Location Errors
TM	Traffic Management
TMC	Traffic Message Channel
TMC	Transportation Management Center or Traffic Management Center
TMS	Transportation Management System or Traffic Management System
TOA	Time of Arrival
TOC	Transportation Operations Center or Traffic Operations Center
TPS	Television Positioning System
TRB	Transportation Research Board (National Research Council)

TSS	Transportation Sensor System
TTFF	Time to First Fix
Tx	Transmit
U	
UHF	Ultra High Frequency
USDOT	United States Department of Transportation
usec, µsec	Microseconds
UTC	Universal Time, Coordinated
UTDOA	Universal Time Difference of Arrival
UTM	Universal Transverse Mercator
UWB	Ultra Wideband
V	
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-Vehicle
VDC	Volts DC
VDOP	Vertical Dilution of Precision
VHF	Very High Frequency
VII	Vehicle-to-Infrastructure Integration
VLSI	Very Large Scale Integration
VPAS	Vehicle Proximity Alert System
VRC	Vehicle Roadside Communications
VSS	Vehicle Speed Sensor
VVI	Vehicle-to-Vehicle Integration
W	
WAAS	Wide Area Augmentation System
WAN	Wide Area Network
WGS-84	World Geodetic System - 1984
WIM	Weigh-in-Motion
WLAN	Wireless Local Area Network

WSS	Wheel Speed Sensor
Z	
ZUPT	Zero Velocity Update

Appendix B - Technical Memorandum on Operations and Maintenance

Technical Memorandum

Maintenance and Operations Considerations for Vehicle Positioning Systems Used for Safety Applications

Introduction

This is a technical memorandum on the activities of Task 4 of Task Order 2 under ARINC's Contract DTFH61-10-D-00015, entitled, "Vehicle Positioning Systems Trade Study for ITS Vehicle Applications". The Task 2 report described the applications requiring vehicle positioning and the Task 3 report presented the results of a market scan related to available and emerging positioning technologies and associated products. In Task 4, a more in-depth analysis of positioning technologies identified in Task 3 as the best candidates to meet application requirements was developed. Another requirement of Task 4 includes addressing operations and maintenance (O&M) requirements and issues related to deploying positioning technology both in roadside equipment (RSE) and in vehicle onboard equipment (OBE). This Technical Memorandum provides some of the findings related O&M of precision positioning equipment. For OBE applications, it addresses differences in maintenance approaches related to vehicle types and associated applications such as public transit, public works, emergency, commercial fleets, and private use.

Types of Maintenance

Positioning systems supporting advanced ITS vehicles and associated applications have finite failure rates and require both preventive and corrective maintenance.

- Preventive maintenance usually consists of verifying the performance of sensors supporting positioning and their associated data processing and communications links.
- Corrective maintenance includes diagnostics to isolate a failure, correction of the failure, verification that the failure has been corrected, and any required recalibration of the system impacted by the failure. There are several approaches to corrective maintenance by vehicle maintenance centers, including:
- "Black Box" packaged functional unit with printed circuit board modules that have circuit components (integrated circuits and electronic components) replacement and either "throw away" or electronic service center repair;
- Removable, plug in module (printed circuit board) replacement and either "throw away" or electronic service center repair.

The total approach to diagnostics and maintenance of advanced ITS vehicles need to be addressed in much the same manner that the military has addressed avionics in aircraft. Having many black boxes integrated through a vehicle network (CAN and Ethernet) is one approach; using larger electronic chassis with a high speed computer bus and functional, plug in modules is another approach. Getting functional, replaceable modules to a cost where they are expendable can reduce both corrective maintenance time and cost. Replacing a black box when the vehicle is taken in for maintenance, and then repairing or remanufacturing the assembly at a separate electronic service center (either at the manufacturer's facilities or a local facilities certified by the manufacturer) reduces the maintenance time associated with the vehicle. The electronic service center would then reassemble and test the black box and return it to inventory at the vehicle service center. One potential drawback is that the black box becomes a "used, refurbished unit" at this time and the cost of repair must be included in its price, although this is a well-established and accepted practice in the automotive industry, especially for higher value components. An alternative approach is expendable units (black boxes or plug in modules) which are replaced at the vehicle maintenance center and discarded.

Roadside Equipment

RSE equipment that provides both position of a vehicle relative to a geo-referenced sensor or the detection of a vehicle at a geo-referenced location in a lane of a corridor may include video detection, radar, and/or LIDAR sensors. Other sensors available for RSE integration include inductive loops, wireless magnetometers, passive acoustic, ultrasonic, and passive IR. (Active IR is utilized in LIDAR). These sensors are currently deployed at intersections and along corridors supporting traffic management and safety.

Typically RSE sensors are maintained by the jurisdictional traffic engineering signal shop. Typically jurisdictions require systems integrators to train their signal technicians, and provide any required test equipment and spare parts. Typically, field repair is conducted by replacement of a failed unit. Some jurisdictions support failed board replacement and component replacement; however, many just do board-level replacement and return the failed board to the manufacturer for repair, or return the complete unit to the manufacturer for repair. It is not unusual that signal shops repair traffic controller boards; however, they may not repair sensors that require special calibration equipment and test ranges. Some manufacturers offer overnight delivery of a replacement unit. There are various types of service agreements guaranteeing maximum repair time by the factory; shorter repair time generally costs more. Manufacturers may have a local repair service that is certified to repair their products, making it more convenient for jurisdictions to coordinate product repair.

In summary, jurisdictions currently maintain RSE sensors and have established processes, typically based on the size of the jurisdiction and numbers of controllers and sensors deployed. Some smaller jurisdictions combine their maintenance (Example Burbank, Glendale, and Pasadena, CA) to reduce maintenance cost.

Vehicle OBE Maintenance

OBE Maintenance by Public Transit Agencies

Depending on the size of the public transit system, several approaches are utilized for maintenance. In larger agencies, such as Houston Metro, preventive and light maintenance activities are performed at bus operating facilities (BOFs) which are located within the route structure of buses assigned to the facilities. There is also a central maintenance facility that supports logistics and major maintenance of the bus fleet. Buses are centrally dispatched and may include both automatic vehicle location and tracking as well as automatic vehicle maintenance monitoring of critical equipment. Some transit agencies use onboard maintenance information recording and "read" the maintenance information when the bus returns to the BOF for daily servicing. It is the responsibility of the driver to report any equipment operational problems to BOF maintenance, and BOF maintenance is responsible for checking equipment associated with performance and safety of the bus. For major repair and servicing, the bus is routed to central maintenance. BOS service technicians have the capability to conduct "black box" testing and replacement. OBE equipment would be sent to central maintenance for repair and return to inventory. Generally central maintenance would send the OBE "black box" to the manufacture or the manufacturer's local, authorized repair shop for servicing. Currently public transit agencies maintain digital radio, GPS/IMU, on-board bus sensors, and HMI equipment. Public transit maintenance technicians are trained by the manufactures of OBE equipment (or the bus manufacturer) on methods for testing, replacement, and verification of performance of a replaced unit. Technicians are also trained in the process to upload software and database upgrades into associated OBE (such as the route guidance equipment). The figure below illustrates larger transit agency maintenance facilities. Smaller transit agencies may have only one facility that is a combination BOF and full maintenance facility. Very small transit agencies may use an independent maintenance service which will have trained service technicians.

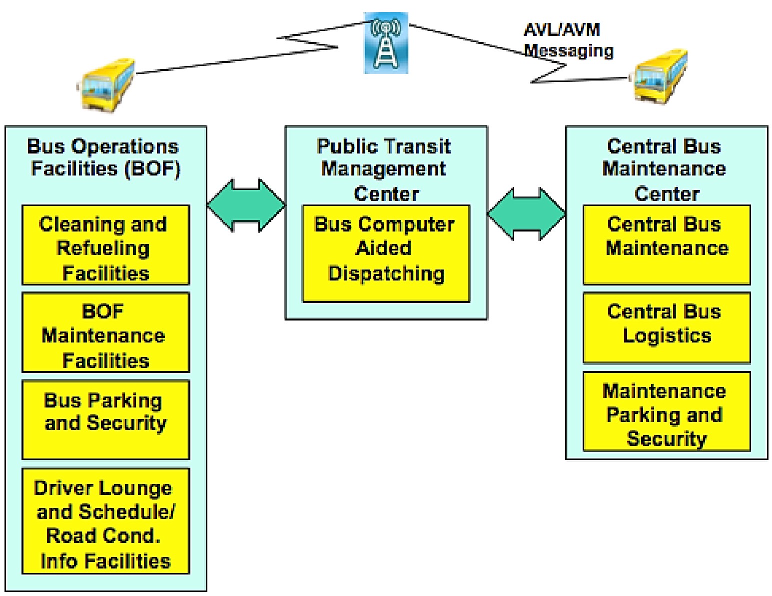


Figure B-1. Example of Maintenance Facilities of a Large Transit Agency
Source: ARINC April 2012

Maintenance by Public School Districts of School Bus OBE

Many public school districts operate in a manner similar to public transit agencies. Buses are picked up by drivers at centers similar to BOFs and returned to the facilities at night.

A central school district maintenance facility conducts repairs of the school buses. Typically the school bus operations center does not support maintenance at the level supported by a public transit agency BOF. Cleaning, refueling, and minor maintenance is supported. Dispatching is usually included in school bus operations facility as well as driver check-in and briefing. Drivers report vehicle operations problems to the dispatcher which coordinates with maintenance to initiate repair. OBE equipment repair would be conducted by central maintenance, which would most likely send the OBE "black box" back to the manufacturer (or his local, authorized repair shop) for servicing and calibration. Central maintenance would maintain spare "black boxes" supporting rapid maintenance.

OBE Maintenance by Taxi and Limo Agencies

Few taxi and limo companies have their own maintenance facilities. In many cases the driver owns the vehicle and is responsible for its maintenance. The taxi and limo companies which have their own vehicles typically use vehicle dealer or a private service garage for vehicle repair. The repair shop would be responsible for training of service technicians, maintaining test equipment required to service OBE, and spare parts. These service centers would most likely use the manufacturer or his local service representative to repair "black boxes" found defective and removed from the vehicle. If the positioning system in the vehicle is utilized to compute fee for miles traveled, then accuracy testing and certification will be required by the jurisdictional authority. Thus an independent test/certification company may be utilized and periodic accuracy test and certification would be conducted. The test and certification company would have to be trained by the manufactures of the equipment and procure the required test hardware and software to support testing. Figure 3.3-1 illustrates the typical repair process. Note that the "black box" independent accuracy certification may be required for units associated with mileage and travel time calculations for service fee purposes, as shown in Figure B-2 below.

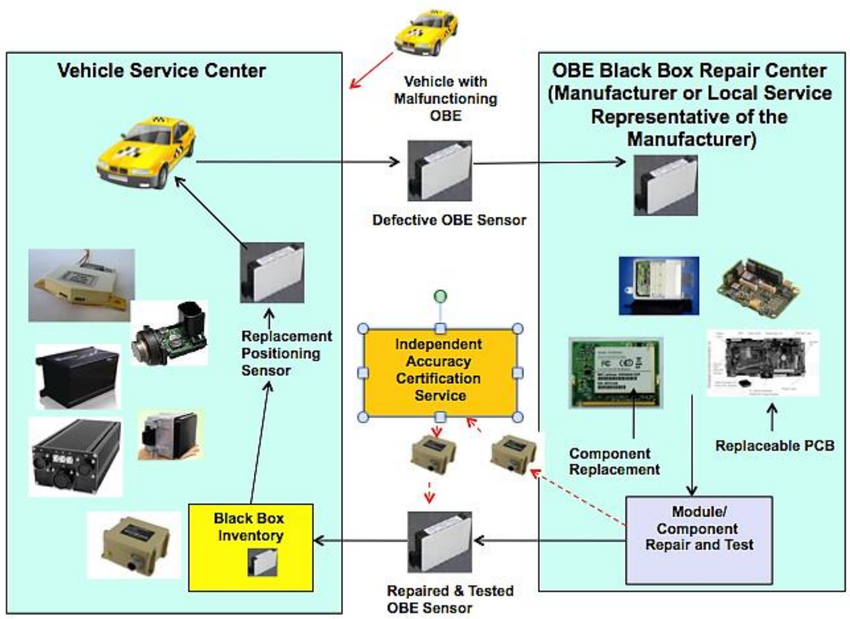


Figure B-2. Maintenance Process Typically Used by Taxi and Limo Companies for OBE Maintenance

(Ref: Federal Highway Administration*,* "Final Report: Vehicle Infrastructure Integration: Proof of Concept Technical Description - Vehicle"; FHWA-JPO-09-017, May 19, 2009 (photos) [87])

The complexity of integrated positioning systems with sensor fusion will most likely require a test and certification interface to the vehicle, with position and time accuracy verification and certification accomplished without removing associated "black boxes." Note that this maintenance process shown in the figure is also applicable to all users who do not have their own service center.

Commercial Vehicle Fleet Maintenance

The maintenance process utilized by commercial vehicle fleets depends on the area serviced. Long haul (18 wheels) vehicles are on the road most of the time and receive maintenance services during trips from truck stops, private service centers, and on-call road service. For commercial delivery services, smaller vehicles are used and they return to the terminal area on a frequent basis; these companies may have their own maintenance centers or use an independent truck service center.

The Federal Motor Carrier Safety Regulations, 49 CFR, Part 393 (Parts and Accessories) and Part 396 (Inspection, Repair, and Maintenance) regulations state:

- A carrier is responsible for ensuring that it properly inspects, repairs, and maintains vehicles under its control;
- A motor vehicle may not be operated when its mechanical condition is likely to cause an accident or breakdown;

- Parts and accessories must be in safe operating condition at all times;
- A vehicle must be maintained according to the vehicle manufacturer's recommended schedule or an improved schedule based on actual operating conditions; and
- Push out windows, emergency doors, and emergency door marking lights in buses must be inspected at least every 90 days.

In addition, states require inspections of commercial vehicles. Positioning systems that are a critical component of vehicle safety will have to be included in commercial vehicle inspections. Thus appropriate test equipment and training of inspectors must be established by businesses licensed by jurisdictions to perform the inspections. Similarly, roadside safety inspections are periodically conducted on commercial vehicles and jurisdictions inspectors will have to be trained and provided appropriate equipment to support testing of OBE that is critical to safety.

Figure B-3 illustrates various maintenance services associated with long haul commercial vehicles and also illustrates a CVO inspection station that could possibly conduct an in route inspection of safety related equipment on the vehicle.

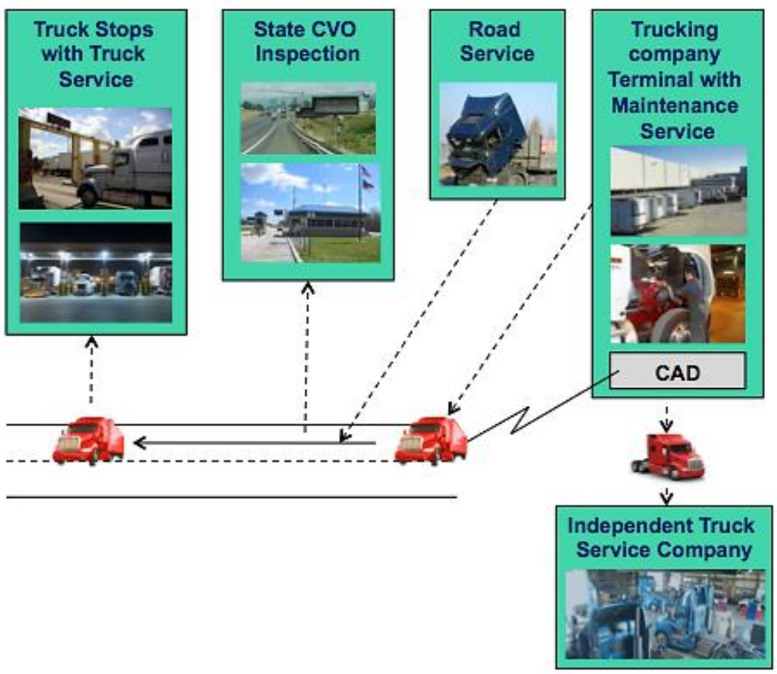


Figure B-3. Examples of Commercial Vehicle Maintenance and Roadside State Inspection
Source: ARINC April 2012

Jurisdictional Vehicles Including Emergency Services and Public Works

Jurisdictions have fleets of vehicles supporting public works and emergency services. Depending on the size of the jurisdiction, they may have a centralized service center for all jurisdictional owned vehicles, may have separate service centers for emergency vehicles and for public works vehicle or may use a private vehicle service. In any case, the vehicles will be periodically inspected and serviced. The inspection would include verifying the operational performance of OBE. Furthermore, jurisdictional vehicles are dispatched. Drivers will report vehicle problems to the dispatcher who will report the problem to vehicle maintenance. Maintenance work orders are processed to execute maintenance. Jurisdictional maintenance will most likely just perform failed "black box" replacement and send the failed unit to the manufacturer (or his local service representative) for repair. Spares inventory of OBE units will be necessary and jurisdictions must receive training on OBE diagnostics, calibration procedures, and use of test equipment. Jurisdictional maintenance will also have to procure any required test equipment to service OBE.

Private Vehicle Maintenance Considerations

Private vehicle owners are much more sensitive to maintenance cost, compared with commercial and jurisdictions users. Therefore, repair cost and vehicle state safety inspection cost must not be significantly increased by installation of advanced OBE in private vehicles. Similarly, cost of updating any software and data bases must be low. Many private vehicle users forgo updating the digital map data base in their current vintage route guidance systems because of the $250+ cost.

During the first term of ownership, most private vehicle owners utilize dealer maintenance service. Reasons for this are:

- During the warranty, only the dealer can supply warranty service;
- Extended warranties are available through the dealer;
- Dealers have factory test/service equipment, factory training of their technicians and maintain factory parts;
- Factory recalls are made through the dealer;
- Dealers usually warrant their maintenance services and have the incentive to maintain good customer relations to support new car sales.

However, during subsequent terms of ownership, vehicle maintenance is generally less consistent, and, unless specific long term warranties are in effect, is often performed by independent repair shops, and in some cases by the owners themselves.

From a private owner's perspective, an advanced OBE should not require any substantial servicing. In recent years, vehicle service intervals have increased from 3000 miles/3 months to about 15K miles/12 months. Annual service intervals usually only involve minor adjustments and fluid changes. Most vehicles require replacement of various wear parts at 30K mile increments, and many go as long as 60K miles without requiring substantial parts replacement. It is not uncommon for most electronic components to last at least the life of the vehicle, and in many cases electronic components are removed from scrapped vehicles and resold as used components. Many parts in this category may be in service for 30 or more years. In general, vehicle owners do not expect to replace major electronic components at all during the first ownership period (about 4-5 years). All electronic systems in modern vehicles include on-board diagnostics that typically identify failures or problems via the vehicle on-board diagnostic system, and the OBE should be no different. This means that the identification of problems and the subsequent repair or replacement of the OBE should be consistent with the established on-board diagnostic processes, and it should contain some ability to determine if it is not operating properly (thus to indicate a problem to the diagnostic system).

OBE and/or sensor service adjustment and/or updating is another matter. Vehicle maintenance by the dealer may include updating of software in electronic units, and may include physical adjustment or calibration, although typically, automotive systems today are self-adjusting, or do not require calibration or other adjustments after leaving the factory. However, when positioning systems are part of a safety-critical functional implementation, they may require periodic performance validation.

In some cases, the OBE will not be able to observe an operational fault or (more likely) calibration problem. This raises an important concern that many calibration issues may not be easily identified in regular operation. This means that some level of calibration tests, such as verifying the accuracy of sensors (accelerometers, yaw sensors, GPS, etc.) is desirable, the process for performing these tests without very sophisticated equipment is uncertain.

It is possible that in some cases a private owner may identify a performance issue with the OBE and will seek service. Depending on the level of sophistication of the OBE, the service may be carried out by an independent technician, or it may require service by the dealer. Investment in test and calibration equipment as well as special training may preclude many private service centers offering OBE service (which will reduce competition to dealer service and drive up cost of maintenance). This is the case for many vehicle systems, especially for newer vehicles.

From a private owners perspective the advanced OBE must:

- Be considered of value and affordable;
- Easy to use;
- Not require expensive database and software updates;
- Require no special maintenance (no frequent servicing and very have very low failure rates (MTBF of 80,000 to 100,000 hrs.) ;
- Not extend routine service wait time;
- Not preclude use of the vehicle if an OBE failure occurs, until it can be scheduled to be repaired;

- Have dealers with proper test and alignment equipment so that a failure can be fixed with high confidence in a single visit;
- Not reduce the pleasure of driving for those who enjoy driving.

Figure B-4 illustrates the private owner options for maintenance. The complexity of maintenance and requirements for special test equipment would preclude the private owner from providing OBU "do it yourself" repair.

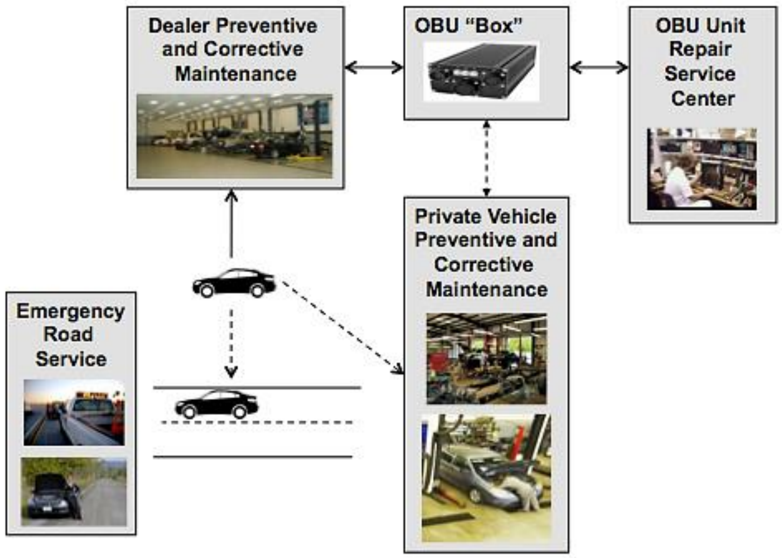


Figure B-4. Private Owner's Options for OBU Service and Repair
Source: ARINC April 2012

Digital Map Maintenance

Digital maps are an integral component of a vehicle navigation system. As digital maps play a greater role in vehicle safety by incorporating identity and locations of corridor safety areas of concern (such as curves and steep inclines requiring a speed reduction, signalized intersections, 4 way stops, speed limit changes, etc.), improvements in quality assurance and configuration management standards and processes are necessary. It will become more important that vehicles have digital maps utilized for safety that are current and represent the latest changes to the infrastructure. Figure B-5 illustrates the process in the European PreVENT project plan supporting digital map distribution, A process of developing quality digital maps, compliant with safety requirements, and convenient and affordable for users to obtain updates is part of the overall maintenance support for positioning systems. Private companies now play an important role in developing and distributing digital maps. As new surveys of urban and rural corridors are required to improve map centerline accuracy and to provide accurate location of safety areas of concern along corridors, cost of developing the new maps will most likely increase. Costs association with map updates will impact whether private users maintain a current digital map data base in their vehicles.

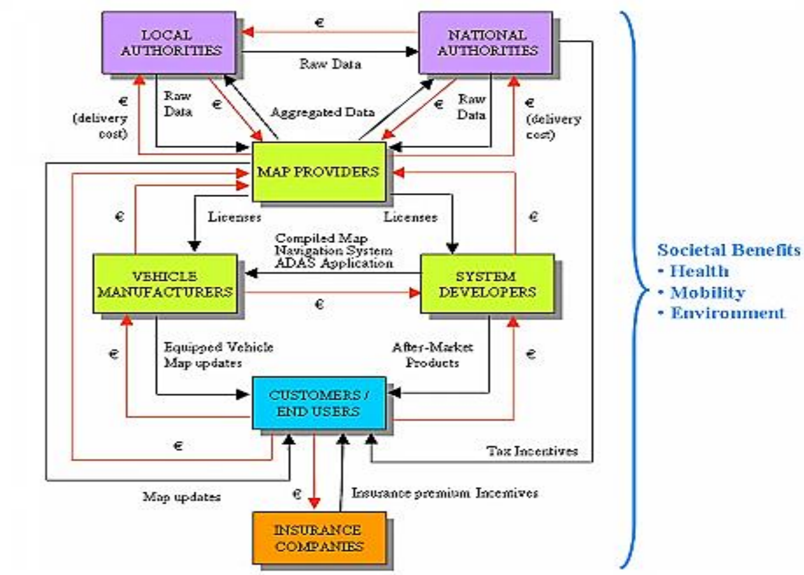


Figure B-5. Digital Map Development and Distribution
(Ref: "Safety Digital Maps Requirements", PReVENT Report PR-12310-SPD-040607-V10-TEL, September 2004 [41])

Broad Considerations Related to Maintenance

With each vehicle manufacturer independently developing their own sensor suite, sensor fusion hardware/software, and target vehicle tracking software, the complexity of the OBEs provides a challenge to independent maintenance service centers. It further provides a challenge for assuring that every advanced ITS vehicle performs with the same location and motion accuracy and utilizes the same collision avoidance strategy that is predictable by all vehicles within the area of concern.

Many of the sensors have both beam and scan patterns that are impacted by installation in a vehicle. Mounting provisions of the sensors allow for horizontal and vertical adjustment. However, it is difficult to manually adjust sensor alignment to provide millimeter accuracy without the aid of a test set up. Also, installation of RF sensors in vehicles can impact both horizontal and vertical beam patterns due to ground plane geometry. Similarly, aftermarket additions to the vehicle by owners could also impact RF and ultrasonic sensor beam patterns. Mud, water, snow, ice or other liquids on radomes of RF sensors and lens protective covers of optical and laser sensors can impact sensor performance. Similarly, build-up of oil with carbon deposits from exhausts can impact RF and optical beam patterns. Determining the deterioration of these beam patterns requires test facility that is capable of mapping the beam. Distorted beam patterns results in false information to the sensor, because it is not obtaining coverage that is expected.

As electronics age, components (such as resistors and capacitors) change value and the calibration of the electronic unit may need adjustment. High temperatures experienced by vehicle electronics in hot climates such as Arizona, can accelerate aging. Some circuits in sensors can be automatically adjusted; however, others require the use of external test equipment. Thus it will be necessary to periodically validate that sensors provide the coverage and measurement accuracy required to support the associated safety application. The frequency of these accuracy and performance validation tests must be established to support vehicle safety. Periodic jurisdictional inspections are currently required in many states. The challenge is the complexity of inspection testing that is necessary to validate sensor and system performances, cost of test equipment, time required to conduct the test and costs over and above the normal inspection fee (which is typically $35 to $50 per year).

To meet the needs for dynamic integrity and reliability, built in test features will be required. The positioning system must be capable of declaring that it is not capable of performing to specification so that a driver or onboard applications do not rely on its positioning information. Unless fully fault tolerant design is utilized (which increases the cost of sensors and associated equipment and possibly destroys the business case), equipment will fail while the driver is enroute; therefore, the overall safety system design (including RSEs and other vehicle OBEs) must accommodate vehicles with failed sensors. Similarly, private owners may not take their vehicles for immediate repair and this situation must be considered.

The aviation industry has a set of standards required for navigation equipment and procedures to be utilized to assure that the navigation equipment meets the specifications. An equivalent of this is needed for the advanced ITS vehicle systems critical to safety applications. Each of the units must have a set of common performance specifications as well as an integrated system performance specification to which “black boxes” and the integrated system are tested and validated. Without this, connected vehicle and infrastructure systems cannot interact with high confidence. All new advanced ITS vehicles should comply with the standards established for each functional unit (black box) and as total integrated system. These same standards will be somehow be utilized for validating performance during vehicle maintenance.

In summary, what is required is:

- National standards for functional elements and at the system level that all manufacturers meet and that the vehicle meets when it is delivered to an owner. This becomes the basis for maintenance testing and performance validation;
- Built in test and diagnostic systems to inform a driver and onboard applications software that his sensor and associated safety system has failed;
- Sensor designs that facilitate accurate but reasonably fast, installed accuracy and performance testing.
- Sensors that can be calibrated and tested at a dealer or independent vehicle service center;

- Design supporting infrequent maintenance and with quickly replicable modules (boxes or PCB modules);
- Initial cost and life cycle servicing cost deemed equivalent to benefit derived by private owners;
- Development of a process for developing, providing quality assurance and configuration management and supporting convenient distribution of GIDs.

Appendix C - Cooperative Positioning Deployment Analysis

One of the key issues in deployment of cooperative system is how quickly the system can provide benefits. Because the existing population of vehicles is large, and the vehicle turnover is slow, the rate that specialized equipment appears in the fleet is rather slow. For independent systems, this is not necessarily an issue since if the vehicle is equipped, then it provides value to the user. For cooperative systems, however, the need for the other vehicles to be equipped in order for the application to operate substantially limits the availability of the benefits of the application.

With 200M cars on the road, the annual vehicle build of 15M units means the vehicle fleet takes at least 13 years to turn over. In fact, however, it takes longer. This is because not every car is retired at 13 years, and not all cars last 13 years. Some last 20-30 years, and some are wrecked the day they leave the showroom.

Figure C-1 shows the growth rate of a feature, for example, a positioning and communications system as a function of time. The blue line shows a typical feature application rate growth curve. This particular growth curve represents a transition from zero to 90% of the annual build being equipped, over a period of 15 years (this is a typical nominal growth rate for the auto industry). The red line represents an integration of 25 years of annual build cycles. In each annual build, the volume of equipped vehicles grows according to the application rate growth, and that cohort of vehicles is then set loose in the field where some die early, some live long, and the average lasts 13 years.

As can be seen in the figure, the fleet takes about 14 years to reach an equipped level of 50%. This line also represents the probability that a vehicle will be equipped. This slow growth rate is primarily a result of the large fleet and the slow vehicle turnover.

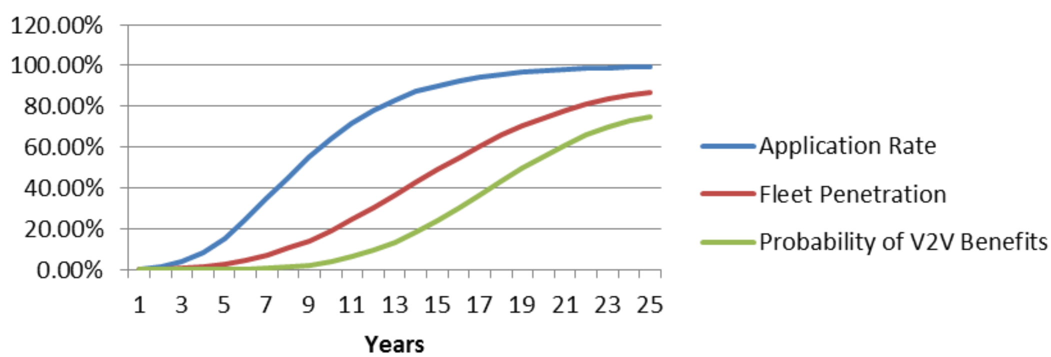


Figure C-1. Growth Rate of ITS Features
Source: ARINC April 2012

The green line represents the probability that any two vehicles that encounter each other will be equipped with the system. This line is a square of the red line. This is because it takes two equipped vehicles to obtain any benefits from the application (the application basically doesn't do anything unless both vehicles are equipped. At 50% fleet penetration this means that the application will have the positioning (and other) information it needs only one in every four encounters. After five years, this probability (effectively the availability of the system) is less than 0.1%. Only after 15 years does it rise to 20%, and after 24 years it finally reaches 90%. This, of course, assumes that the industry continues to produce these systems through the early years when there is effectively zero application availability.

Appendix D - Detailed Positioning Requirements Analysis

The decision for an application to take action generally requires determining a point at which the action should be taken such that known events can occur before the actual safety event is reached. For example, if the safety event is a fixed obstacle in the road, and the objective of the application is to warn the driver, then the application must issue the warning sufficiently in advance that the driver has time to perceive the warning, react and then control the vehicle, for example, being it to a stop.

The AASHTO Green Book describes two human factors related metrics: the Stopping Sight Distance and the Decision Sight Distance. The sight distance is the distance required to perceive the hazard, assuming that the user was expecting it. The decision sight distance includes an added distance associated with the time that the user needs to perceive and understand the hazard. In general, if the driver has already been alerted to a potential hazard, then they will perceive it more rapidly that if they happen upon it with no advance pre-set alertness. Decision sight distance is applied where numerous conflicts, pedestrians, various vehicle types, design features, complex control, intense land use, and topographic conditions must be addressed by the driver. Stopping sight distance is applied where only one obstacle must be seen in the roadway and dealt with.

Because the distance traveled depends on speed, the sight distance and decision sight distance are typically normalized to a time value.

The perception-reaction time for a driver is often broken down into the four components that are assumed to make up the perception reaction time. These are referred to as the PIEV time or process.

- Perception the time to see or discern an object or event
- Intellection the time to understand the implications of the object's presence or event
- Emotion the time to decide how to react
- Volition the time to initiate the action, for example, the time to engage the brakes

The Sight Distance is given by:

$$SD = 1.47\ Vt + \frac{V^2}{30\,(f \pm g)}$$

Where V is the speed in mph, T is the perception and reaction time, f is the coefficient of friction and g is the grade.

(Ref: "Discussion Paper No. 8, A Stopping Sight Distance and Decision Sight Distance", prepared for Oregon Department of Transportation, Salem, Oregon by the Kiewit Center for Infrastructure and Transportation, Oregon State University Corvallis, Oregon September 2004 [52])

For the following analysis we have assumed that g=0 (flat grade).

The reference above also provides the following table of coefficients of friction published by AASHTO.

Design Speed		Running Speed		1990 and 1994 AASHTO Coeff. of Friction for f_{WET}	AASHTO Coeff. of Friction for trucks, f_{TR}	Acceptable Deceleration for Trucks, a_{TR} ft/sec^2
30 kph	(20 mph)	32 kph	(20 mph)	0.40	0.25	8.1
50 kph	(30 mph)	45 kph	(28 mph)	0.35	0.21	6.8
65 kph	(40 mph)	58 kph	(36 mph)	0.32	0.19	6.1
80 kph	(50 mph)	71 kph	(44 mph)	0.30	0.18	5.8
100 kph	(60 mph)	84 kph	(52 mph)	0.29	0.17	5.5
115 kph	(70 mph)	93 kph	(58 mph)	0.28	0.16	5.1

Figure D-2. Table of Coefficients of Friction

Ref: "Discussion Paper No. 8, A Stopping Sight Distance and Decision Sight Distance", prepared for Oregon Department of Transportation, Salem, Oregon by the Kiewit Center for Infrastructure and Transportation, Oregon State University Corvallis, Oregon September 2004 [52]

There is also a substantial difference between normal braking and emergency braking. The above reference provides the following table.

Speed	Stopping Sight Distance, (ft.)		Typical Emergency Stopping Distance, (ft.)	
Design Speed (mph)	Calculated (2.5^s, a=11.2 FPS^2)	Design (2.5^s, a)	Wet Pave. (1^s, f_{wet})	Dry Pave. (1^s, f_{dry})
20	111.9	115	63	52
25	151.9	155	92	71
30	196.7	200	130	94
35	246.2	250	172	120
40	300.6	305	225	148
45	359.8	360	284	179
50	423.8	425	357	212
55	492.4	495	417	249
60	566.0	570	495	288
65	644.4	645	581	330
70	727.6	730	686	375

Figure D-3. Difference Between Normal Braking and Emergency Braking
Ref: "Discussion Paper No. 8, A Stopping Sight Distance and Decision Sight Distance", prepared for Oregon Department of Transportation, Salem, Oregon by the Kiewit Center for Infrastructure and Transportation, Oregon State University Corvallis, Oregon September 2004 [52]

Since there is a wide variation in perception time, and braking level, we can use this as a variable in developing false positive and false negative application event distances. The table below provides an analysis at 60 mph (100 kph) that compares the SSD and DSD values based on various values for perception/reaction time and braking level.

For the false positive case, we have assumed worst case reaction time values of 2 seconds for SSD and 2.5 seconds for DSD. We have also assumed the nominal .34 g deceleration value recommended by the AASHTO Green Book. For the nominal case, we have assumed a perception/ reaction time of 1.5 seconds for SSD, and 2 seconds for DSD. This is based on the results of several studies carried out on reaction time and summarized in the above reference. The results are provided below.

Recent studies have checked the validity of 2.5 seconds as the design perception reaction time. Four recent studies have shown maximums of 1.9 seconds as the perception-reaction time for an 85th percentile time and about 2.5 seconds as the 95th percentile time.

Brake Reaction Times Studies

	85th	95th
Gazis et al. (1)	1.48	1.75
Wortman et al. (2)	1.80	2.35
Chang et al. (3)	1.90	2.50
Sivak et al. (4)	1.78	2.40

(1) Gazis, D.R, et al., "The Problem of the Amber Signal in Traffic Flow," Operations Research 8, March-April 1960.

(2) Wortman, R.H., and J.S. Matthias, "Evaluation of Driver Behavior at Signalized Intersections," Transportation Research Record 904, T.R.B, Washington, D.C., 1983.

(3) Chang, M.S, et al., "Timing Traffic Signal Change Intervals Based on Driver Behavior," T.R. Record 1027, T.R.B, Washington, D.C., 1985

(4) Sivak, M., et al, "Radar Measured Reaction Times of Unalerted Drivers to Brake Signals," Perceptual Motor Skills 55, 1982.

Figure D-4. Reaction Time Study Results

We have also assumed a nominal deceleration level of 0.51 g which is the average between the maximum of 0.7 g and the nominal value used by AASHTO.

For the false negative situation we have assumed emergency braking levels of twice the nominal AASHTO value (this is based on the AASHTO observations that emergency braking distances are about half the nominal braking distances). We have also assumed that the reaction times are shorter by about 0.5 second from the nominal case.

The reaction and stopping components of the SSD and DSD are provided for the different cases in the table below.

As described in the body of the report, if the application acts no earlier early than the false positive point, then it will not be perceived as acting too early, and it if acts no later than the false negative point, then it will not impose an undue danger to the driver. Thus the overall accuracy requirement for this particular situation is simply the difference in distance between the false positive point and the false negative point. This represents the entire diameter of the tolerable error circle (or sphere, in three dimensions), so this value must be divided by two to obtain the error radius.

Speed = 60 mph		False Positive Case		Nominal Case		False Negative Case	
		SSD	DSD	SSD	DSD	SSD	DSD
Perception Reaction Time (Sec)	1.00					88	
	1.50			132.3			132.3
	2.00	176.4			176.4	1.1	1.2
	2.50		220.5				
Deceleration Level (g)	0.34	352.9	352.9				
	0.51			235.3	235.3		
	0.68					176.5	176.5
Total Distances (ft)		529.3	573.4	367.6	411.7	264.7	308.8

Distance Between False Positive and False Negative Points	264.7	Feet
	80.7	Meters

Required Accuracy Radius	132.3	Feet
	40.3	Meters

Source: ARINC April 2012

At 30 mph this table is substantially different. It is important to note that the stopping distances change substantially at different speeds, and the reactions times correspond to much smaller distances. This means that lower speeds impose higher levels of positioning accuracy.

Speed=30 mph		False Positive Case		Nominal Case		False Negative Case	
		SSD	DSD	SSD	DSD	SSD	DSD
Perception Reaction Time (Sec)	1.00					44	
	1.50			66.2			66.2
	2.00	88.2			88.2		
	2.50		110.3				
Deceleration Level (g)	0.34	88.2	88.2				
	0.51			58.8	58.8		
	0.68					44.1	44.1
Total Distances(ft)		176.4	198.5	125.0	147.0	88.2	110.3

Distance Between False Positive and False Negative Points	88.2	Feet
	26.9	Meters

Required Accuracy Radius	44.1	Feet
	13.4	Meters

Appendix E - Assumed System Architecture

Roadside Equipment (RSE)

Roadside Equipment is defined as that which is installed on the roadside and provides the interconnect link between infrastructure and the vehicle. The RSE may be permanently installed along the roadside or at an intersection or may be temporarily installed to support road work or a major incident (such as a HAZMAT spill).

As RSE technology evolves, it will presumably evolve to a modular architecture with "plug in" functional modules, similar to the 2070 traffic controller which utilizes 4U VME bus modules. It is also possible that the RSE may evolve into a communications hub, that is configurable by using "plug in" modules such as communications modem/transceivers, fire wall/routing and Ethernet switch, "connected vehicle-infrastructure" applications processer(s), and communications manager modules with the traffic controller being a standalone unit with Ethernet interface to the RSU electronic chassis. Current terminology uses RSE to designate all electronic units (hardware and software with interconnect cabling and power) at a roadside location that supports communications from roadside to the vehicle and associated applications.

The RSE includes a variety of functional elements, and will be configured to meet the operational needs of the specific application. The following functional elements may be included in an RSE:

- Classical Traffic Controller Functions:
  - Signal Phase and Timing management and control;
  - Traffic Responsive SPAT adjustments;
  - Controller status and SPAT reporting to the TMC;
  - Timing plan update message receipts from the TMC and update execution;
  - Visual signal activation and deactivation (Signal Head and PED Displays);
  - Audible PED phase signal activation and deactivation;
  - Conflict monitoring and conflict prevention (Fail Safe);
  - Signal Call sensors signal processing;
  - PED Call devices signal processing;
  - Time Referencing and Synchronization (GPS Time);
  - Statistical data gathering and reporting;
  - Signal Preempt and Signal Priority Call and "SMART" Execution (SMART execution includes determining of a transit vehicle is off schedule by a specified amount justifying TSP and if multiple emergency vehicles are involved in the preempt Call);
  - Signal Phase extension of preemption to accommodate TSP or Emergency Preempt Call;

- Extend all Red Phase to prevent an intersection collision by a red-light violating vehicle;
- Sensor Interface: Inductive Loops, Video Detection, RADAR, Ultrasonic, IR, Passive Acoustic, LIDAR, etc.

- Communications Functions:
  - Ethernet Switch/Router for local sensors, traffic controller, and interface to the TMC for wire line or optical interconnections; firewall router functions if wireless interconnections are utilized;
  - Wireless modem/transceivers supporting wireless network interfaces at the roadside location. (This would include wireless Ethernet interfaces for local sensors, DSRC wireless interface, and any Ethernet WAN interface utilized to link the RSE with the TMC);
  - Communications Management and Security Functions.
- Advanced ITS Functions:
  - Applications Processing associated with advanced ITS applications, including those associated with this project.
  - Timing synchronization and coordination of functions. (With extended function RSE, time coordination and synchronization will be at a higher level than traffic controller.).

Figure E-1 illustrates an RSE architecture where the traffic controller is a separate unit (such as a 2070 traffic controller). Figure E-2 illustrates architecture of an advanced RSE where functional modules are utilized to configure all functions associated with the RSE, except for the external roadside sensors and antenna interconnections to wireless transceiver/modems.

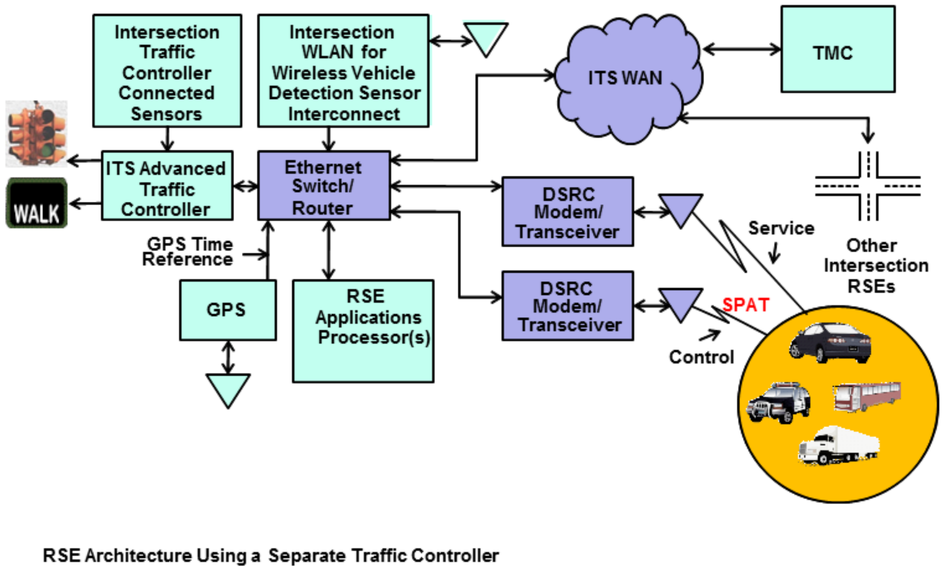


Figure E-1. RSE Architecture with a Separate Traffic Controller Interfaced Via an Ethernet 100BaseT Ethernet Connection to the Remaining RSE via an Ethernet Switch/Router
Source: ARINC April 2012

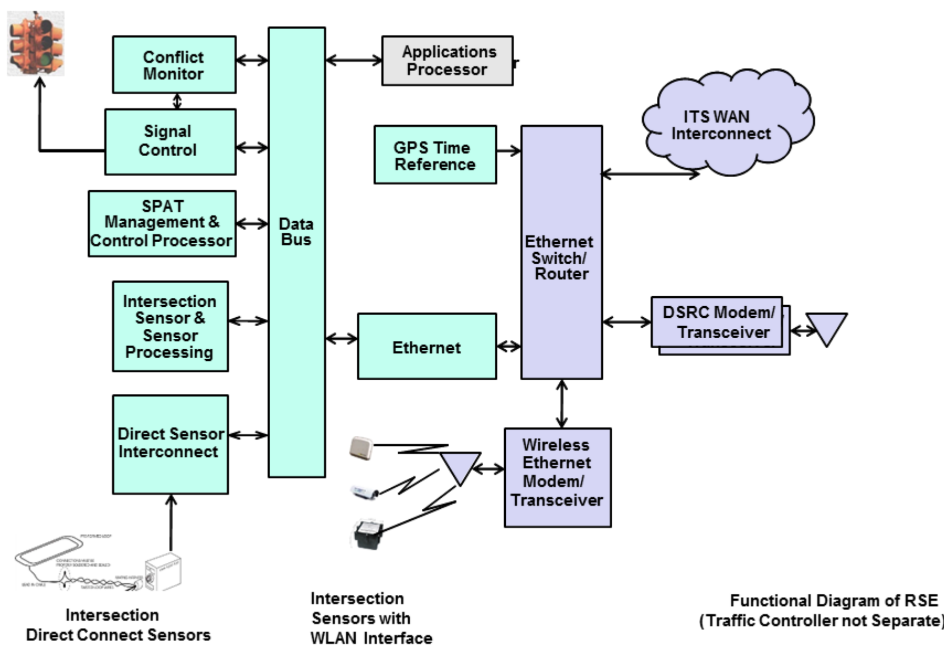


Figure E-2. RSE Architecture with Modular Construction
Source: ARINC April 2012

Onboard Equipment Architecture

Vehicles are becoming increasingly integrated, and increasingly electronic. Typically the components in any subsystem are interconnected using some form of serial data bus. However, because many vehicle systems operate in real time (engine and power train controllers, safety systems, etc., the serial buses are typically designed to provide deterministic temporal behavior, assurance of message delivery, assured non-conflicting messages, assured time, and electromagnetic interference (EMI) resilience. This limits the applicability of commonly known serial buses used in the computing industry (Ethernet, USB, etc.). Instead automotive systems use time synchronized serial protocols such as SAE J1850, and one wire Local Interconnect Network (LIN bus), the SAE J1587 truck diagnostic bus, and the Car Area Network (CAN bus). The CAN bus was originally developed by Robert Bosch Corporation, but it is now licensed universally across the industry. The CAN bus 2.0 is defined by SAE J1939. There are also specialized bus protocols for highly critical applications, for example, the time triggered protocol. Most of these data buses are wire based, but other than meeting vehicle environmental requirements, there is no reason the physical layer could not be implemented using optical fiber, which has an inherent resistance to EMI.

Except for very complex and expensive systems, wireless communications is generally not guaranteed in terms of timing or in terms of absolute message reliability. Some systems are designed to compensate for this through message redundancy, repeats, etc. (e.g., TCP/IP). As a result, many systems based on wireless data communications make use of Ethernet type protocols to network components associated with the wireless system. These applications are generally never used for real time control or operational aspects, and are not used for safety systems. For example, the US Marines' Expeditionary Fighting Vehicle (EFV) uses a PC-104 based embedded processor connected to various information peripherals using an Ethernet bus. These systems are effectively information systems for the occupants, and for networking between vehicles and command centers, and, are not directly engaged in vehicle operations. A similar system was used for the on-board equipment in the US DOT VII Proof of Concept project.

Figure E-3 illustrates the ruggedized switch/router utilized in the EFV and configured from commercial, off the shelf (COTS) modules.

Figure E-3. Mobile Ethernet Switch Router Utilized in the USMC Expeditionary Fighting Vehicle
(Ref: Southworth, M., “EFV Keeps Pace with Ethernet to Actualize Net-centric Warfare”, *Military Embedded Systems*, August 14, 2009 [89])

Test vehicles used by the ERTICO Cooperative Vehicle-Infrastructure System (CVIS) program in Europe also utilized a ruggedized Ethernet Switch Router, which is shown in Figure E-4 to support the Continuous Air Interface for Long and Medium Distance Operations (CALM).

Figure E-4. European CVIS Mobile Switch Router
(Ref: “Reference Execution Platform”, CVIS Project Document D.CVIS.4.1, June 30, 2009 [72])

Figure E-5 illustrates the European CVIS project OBE architecture which utilizes Ethernet and a firewall gateway/bridge to the vehicle CAN bus. Other vehicle architectures include device design with direct CAN bus interface.

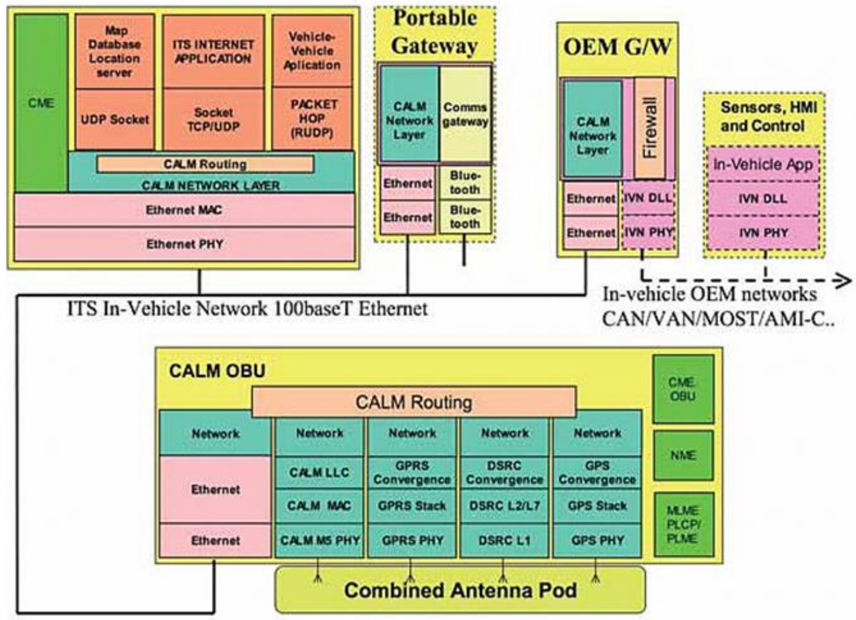


Figure E-5. ERTICO CVIS OBE Architecture Illustrating CALM
Source: ARINC April 2012

A critical aspect of the vehicle architecture is to protect sensitive vehicle operational systems from disruption. This disruption may come from interference, or from intentionally or unintentionally misbehaving devices, or from spoofing messages sent by hackers. For example, in the CVIS architecture promoted by CALM, the OEM Gateway includes a "firewall" which is intended to isolate the vehicle systems from the ITS system.

The VII Proof of concept demonstration in Detroit implemented this in a different way. The OBE architecture for this application is shown in Figure E-6. In this system, the vehicle CAN bus was connected to the ITS processor, and a specialized software component read the CAN bus messages directly. This software included specialized interface code that was configured to each specific vehicle type (since all CANBUS implementations are different). The Vehicle Interface system then converted the vehicle parameters into a common format that was useful to the ITS applications (vehicles use different units, scale factors, etc.). This system was read-only, so that there was no way to place an erroneous CAN bus message into the system and thereby disrupt the vehicle operations. This system also uses specialized software systems that provide set of shared resources to the various ITS applications. In a typical ITS system, all applications will, for example, require access to vehicle position, communications, security, and the HMI in the vehicle. Providing the vehicle position to multiple applications is a simple matter; arbitrating a prioritizing access to the HMI, so, for example, a safety critical application can display a warning over a convenience application is more challenging. This task becomes especially complex when dealing with competing safety warnings.

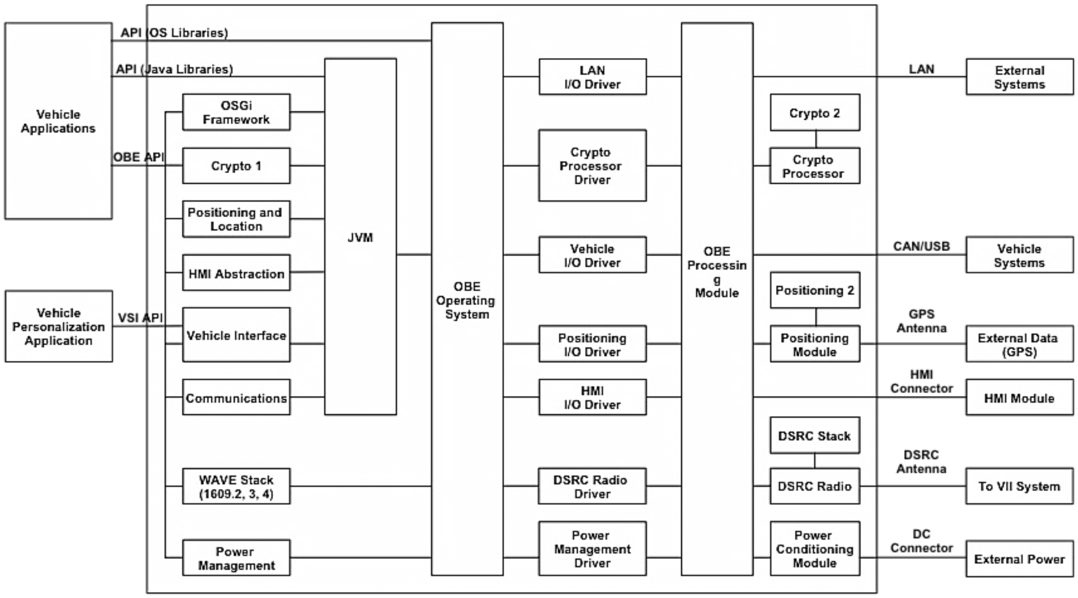


Figure E-6. VII Proof of Concept OBE Architecture
Source: ARINC April 2012

Figure E-7 illustrates a general OBE architecture that represents a system capable of supporting most anticipated ITS applications.

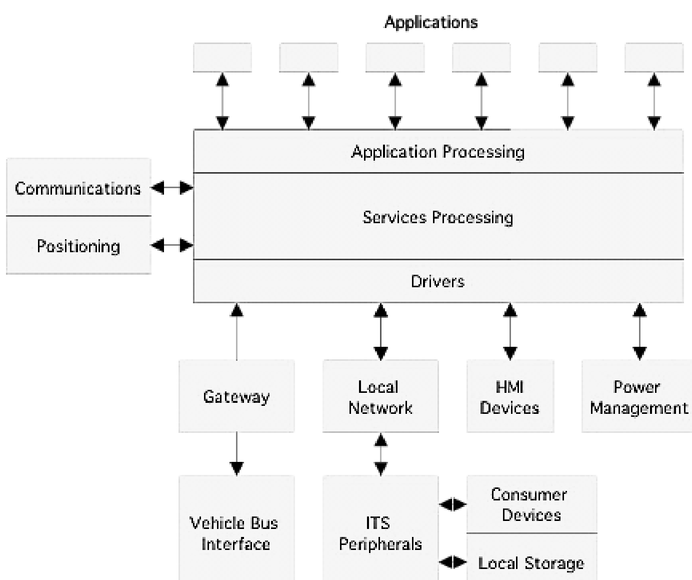


Figure E-7. General ITS OBE Architecture
Source: ARINC April 2012

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free "Help Line" 866-367-7487
www.its.dot.gov

Publication FHWA-JPO-12-064

U.S. Department of Transportation