

CAMP

Enhanced Digital Maps

DAIMLERCHRYSLER

DaimlerChrysler Research and Technology North America, Inc.



NAVTEQ

IVI Light Vehicle Enabling Research Program

Enhanced Digital Mapping Project

Final Report

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TABLE OF CONTENTS

Executive Summary

1 Introduction.....	1-1
1.1 Report Layout.....	1-1
1.2 Overall EDMap Plan.....	1-1
1.3 Motivation and Background.....	1-2
1.3.1 Map Database as a Sensor	1-2
1.3.2 Current Map Database and Vehicle Positioning Capability	1-4
1.3.3 Navigation System Availability	1-5
1.4 Tasks and Results Summary	1-5
1.4.1 Task 1 – Identification of Intelligent Vehicle Applications Enabled by Mapping Technology	1-6
1.4.2 Task 2 – Determination of Application Attribute Requirements	1-7
1.4.3 Task 3 – Definition of Final Safety Demonstration.....	1-9
1.4.4 Task 4 – Data Collection and Maintainability	1-10
1.4.5 Task 5 – Test Site Mapping/NAVTEQ.....	1-12
1.4.6 Task 6 – Demonstrator Vehicles	1-12
1.4.7 Task 7 – Enhanced Digital Map Evaluation	1-14
1.4.8 Task 8 – Deployment Analysis	1-14
1.4.9 Task 9 – Final Report and Recommendations	1-15
1.5 References.....	1-16
2 Application and Mapplet Evaluation Results.....	2-1
2.1 Curve Speed Assistant.....	2-2
2.1.1 Introduction	2-2
2.1.2 Evaluation Criteria and Test Areas.....	2-2
2.1.3 Performance Analysis	2-4
2.1.4 Possible Deployment Options and Potential Safety Benefits	2-16
2.1.5 References	2-17
2.2 Stop Sign Assistant	2-18
2.2.1 Application Description	2-18
2.2.2 Application Results.....	2-19
2.2.3 Possible Deployment Options and Potential Benefits	2-20

2.2.4	Safety Benefit.....	2-28
2.2.5	Mapplets for the SSA.....	2-29
2.3	Forward Collision Warning	2-31
2.3.1	Introduction	2-31
2.3.2	Application Behavior	2-33
2.3.3	Application Evaluation	2-35
2.3.4	Mapplet Evaluation.....	2-37
2.3.5	Vehicle Positioning Performance and Analysis	2-40
2.3.6	Possible Deployment Options and Potential Safety Benefits	2-43
2.3.7	References	2-44
2.4	Traffic Signal Assistant	2-45
2.4.1	Application Performance and Results.....	2-45
2.4.2	Mapplet Analysis.....	2-46
2.4.3	Vehicle Positioning Performance and Analysis	2-52
2.4.4	Possible Deployment Options and Potential Safety Benefits	2-53
2.5	Lane Following Assistant	2-55
2.5.1	Application Performance and Results.....	2-55
2.5.2	Mapplet Analysis.....	2-56
2.5.3	Vehicle Positioning Performance and Analysis	2-66
2.5.4	Possible Deployment Options and Potential Safety Benefits	2-67
3	Map Database	3-1
3.1	Introduction.....	3-1
3.2	EDMap Database Creation	3-2
3.2.1	Definition of Terms	3-2
3.2.2	Near-term Database.....	3-3
3.2.3	Mid-term Database.....	3-9
3.3	Deployment Constraints and Potential Mitigations by Application	3-16
3.3.1	Maintainability	3-16
3.3.2	Limitations and Constraints	3-17
3.4	Database Creation Effort	3-20
3.4.1	Curve Speed Assistant (CSA-W).....	3-21
3.4.2	Stop Sign Assistant-W (SSA).....	3-23
3.4.3	Curve Speed Assistant (CSA-C).....	3-24
3.4.4	Forward Collision Warning (FCW-W).....	3-26
3.4.5	Lane Following Assistant (LFA-W).....	3-27
3.4.6	Traffic Signal Assistant (TSA-W).....	3-28

3.4.7	Stop Sign Assistant (SSA-C)	3-29
3.4.8	Revised Effort Summary	3-30
3.4.9	Effort Mitigation	3-31
3.4.10	Equipment Costs	3-34
3.4.11	Potential Rollout Scenarios	3-34
3.4.12	Future Work.....	3-37
3.5	Quality Metrics.....	3-39
3.5.1	Approach.....	3-39
3.5.2	Sampling.....	3-39
3.5.3	Geometric Assessment Methodology	3-39
3.5.4	Relative Accuracy Geometry Results	3-41
3.5.5	Attribute Assessment Methodology	3-44
3.5.6	Attribute Results.....	3-45
4	Positioning Systems	4-1
4.1	Introduction.....	4-1
4.2	Road-level Vehicle Positioning	4-3
4.2.1	NTBox Positioning Device.....	4-3
4.2.2	Road-Level Positioning Performance	4-4
4.3	Lane-level Vehicle Positioning	4-6
4.3.1	Honeywell Prototype Automotive Positioning Sensor (PAPS) Positioning Device	4-6
4.3.2	Lane-Level Positioning Performance	4-7
4.4	Future Positioning System Improvements.....	4-13
4.4.1	GNSS Developments	4-13
4.4.2	IMU Developments	4-14
5	Summary and Conclusions	5-1
5.1	Introduction.....	5-1
5.2	Mapplet Optimization	5-1
5.3	Vehicle Positioning	5-2
5.4	Applications as a Guide	5-4
5.5	Future Topics	5-5
5.5.1	Hybrid Map Database.....	5-5
5.5.2	Vehicle Positioning to support WHICHLANE applications	5-5
5.5.3	Stopping Location Collection and Maintenance using Probe Data.....	5-5

5.5.4 Map database update.....5-6
5.5.5 Quality Indicator Mapplet.....5-6
5.6 Acknowledgements.....5-7

Appendix A: Task 1 - Application Selection

Appendix B: Task 2 - Data Analysis Tools

Appendix C: Task 4 - Data Collection and Mapping

Appendix D: Task 6 - OEM Test Vehicle Setups

Appendix E: Quality Assessment Report

Appendix F: Curve Speed Assistant Evaluation

Appendix G: Forward Collision Warning Evaluation

Appendix H: Common Vehicle Components and Architecture

Appendix I: Task 8A - Deployment Issues

Appendix J: Task 8B - External Deployment Factors

LIST OF FIGURES

Figure 1: Likely Global Navigation Satellite System (GNSS) capability timelinexiii

Figure 2: Applications by type and relative effort multiplier xvii

Figure 3: Database efforts by application considering target road typesxx

Figure 4: Composite database efforts by application considering target road typesxxi

Figure 1-1 Road network with enhanced map attributes..... 1-4

Figure 1-2: EDMap work tasks 1-5

Figure 1-3: Task 4 approach..... 1-10

Figure 1-4: Proportion of collection, processing, and distribution for navigation,
near-term and mid-term efforts 1-11

Figure 1-5: Demonstrator vehicle architecture highlighting the common components
and OEM specific components 1-13

Figure 2-1: Palo Alto GM and Ford CSA demo routes.....2-3

Figure 2-2: California Route 17 test area (left) and Michigan demo route (right)2-3

Figure 2-3: CSA-C curve following the California Sandhill Road ramp2-7

Figure 2-4: Incorrect near-term curvature representation.....2-9

Figure 2-5: Sandhill Road ramp to southbound I-280 geometry..... 2-10

Figure 2-6: Sandhill Road ramp to southbound I-280 curvature (1/m).....2-10

Figure 2-7: Map-matching incorrect near ramps..... 2-15

Figure 2-8: Lane-level preview aiding 2-16

Figure 2-9: Near-term distance to the stop sign at 21 locations in Palo Alto 2-22

Figure 2-10: GPS satellite visibility 2-23

Figure 2-11: Mid-term positioning sensor route traceability
along the Palo Alto demonstration route 2-24

Figure 2-12: Locations of the ADASRP reported vehicle position status 2-25

Figure 2-13: Poor geometry and PAPS deviated locations 2-26

Figure 2-14: Mid-term data position accuracy improvement 2-27

Figure 2-15: Forward collision warning block diagram..... 2-31

Figure 2-16: California (left) and Michigan (right) FCW demonstration
and evaluation routes 2-32

Figure 2-17: Correct target selection and correct target rejection 2-34

Figure 2-18: Incorrect target selection (a) and incorrect target rejection (b) 2-35

Figure 2-19: INS performance during day one of California demonstration..... 2-41

Figure 2-20: Position errors for multiple trips on the California demonstration route 2-42

Figure 2-21: Control/no-control signals 2-46

Figure 2-22: Traffic Signal Assistant evaluation route in California and Michigan2-47

Figure 2-23: Distribution of stopping location errors in CA and MI.....2-48

Figure 2-24: Signal heads and map-reported position disagree,
although the correct signal indication is still identified2-50

Figure 2-25: System comparison at complex intersections2-51

Figure 2-26: Challenging signal configurations2-51

Figure 2-27: Signal heads that cannot be detected with the current system.....2-52

Figure 2-28: Effects of GPS error on signal search boxes2-53

Figure 2-29: California (left) and Michigan (right) demonstration and evaluation route2-56

Figure 2-30: Typical lane width differences (Page Mill Rd.)2-56

Figure 2-31: Differences between vision and Map/GPS systems2-58

Figure 2-32: Section between 400 m and 600 m exceeds allowed error tolerance2-59

Figure 2-33: Genuine warning; vision lane tracker and Map/GPS system
examine the vehicle leaving the lane2-60

Figure 2-34: Vehicle is leaving the lane and Map/GPS system reports
crossing of lane boundaries early2-61

Figure 2-35: Map/GPS system issues a warning; vision system shows
vehicle well within the lane2-62

Figure 2-36: Average map error examined on Palo Alto evaluation route.....2-62

Figure 2-37: M-5 north and south improvements.....2-63

Figure 2-38: Curvature on 4.5 km segment of I-280 (6 traces).....2-64

Figure 2-39: Changing GPS error on a typical drive on the Palo Alto evaluation route
(total length: 21.9 km)2-66

Figure 3-1: Near-term data collection system configuration3-3

Figure 3-2: Process to illustrate near-term database creation process3-4

Figure 3-3: Illustration of EDMap ZELink, GPS traces, and the resulting spline3-5

Figure 3-4: Curvature porcupines for a road segment3-7

Figure 3-5: Midcover events in editor display3-8

Figure 3-6: Mid-term data collection system configuration3-10

Figure 3-7: Process flow diagram for lane geometry creation3-11

Figure 3-8: Lane width creation using multiple data sources.....3-13

Figure 3-9: Midcover and image cover points at a signalized intersection3-14

Figure 3-10: Traffic signal placement by triangulation3-15

Figure 3-11: Proportion of collection, processing, and distribution for navigation,
near-term, and mid-term efforts determined in Task 4 (April 2003).....3-20

Figure 3-12: Relative database creation efforts (March 2004)3-31

Figure 3-13: Relative database creation efforts using road type mitigation (May 2004) 3-34

Figure 3-14: Absolute and relative accuracy 3-40

Figure 3-15: Near-term geometry pass rates..... 3-41

Figure 3-16: Mid-term geometry pass rates (original QA method) 3-42

Figure 3-17: Relative accuracy result using new ICP method vs. original QA method 3-43

Figure 3-18: Mid-term geometry pass rates using new relative accuracy method (ICP)..... 3-44

Figure 3-19: Link attributes: pass/fail by subgroup..... 3-46

Figure 3-20: Types of point attribute errors..... 3-46

Figure 3-21: Positional accuracy of point attributes 3-47

Figure 4-1: Common vehicle side positioning system structure 4-2

Figure 4-2: NTBox system block diagram 4-3

Figure 4-3: NTBox road-level GPS receiver 4-4

Figure 4-4: Road-level positioning performance on the Toyota Palo Alto demonstration route 4-4

Figure 4-5: Coast Guard DGPS correction (on/off) – Station ID 46 SNR34 used during this test..... 4-5

Figure 4-6: Honeywell PAPS positioning sensor 4-6

Figure 4-7: % time spent in standard deviation categories – March 24-26, 2004 4-8

Figure 4-8: Best run of March demonstration drives..... 4-9

Figure 4-9: Typical overpass that causes total satellite outage and results in high GPS errors 4-10

Figure 4-10: Overhead road sign that would lead to a partial satellite blockage 4-11

Figure 4-11: Heavy tree cover on residential streets blocks satellite signals..... 4-11

Figure 4-12: Lane-level position system drifts under adverse conditions 4-12

Figure 4-13: Accuracy Capabilities by Year for Various GNSS Operating Modes..... 4-14

Figure 4-14: Free inertial drift of three IMU classes (gyro only) 4-15

Figure 5-1: Results of mapplet optimization with regard to content and extent 5-2

Figure 5-2: GNSS timeline with attention called to 1 to 0.5 m positioning required for WHICHLANE applications 5-3

LIST OF TABLES

Table 1: Error budget for WHICHLANE and WHEREINLANE applicationsxiii

Table 2: Road-type distribution and application usage metrics xix

Table 3: Application distribution and potential developmental steps of safety applications xxiv

Table 1-1: High safety potential applications using maps1-7

Table 1-2: Demonstration applications selected1-9

Table 2-1: Mapplet requirements2-5

Table 2-2: Curve speed curve warning performance.....2-6

Table 2-3: Deployment constraints2-28

Table 2-4: Potential mitigations to deployment constraints2-29

Table 2-5: Possible disadvantages to potential mitigations2-29

Table 2-6: Scores of EDMap-based versus yaw-rate-based target selection2-36

Table 2-7: Mean error and its standard deviation for the CA and MI evaluation trips2-38

Table 2-8: Error distributions at 60 m and 120 m preview distances
for the CA and MI Trips2-38

Table 2-9: Mapplet requirements2-52

Table 2-10: Lane Following Assistant mapplet requirements2-65

Table 3-1: CSA-W mapplet requirements3-22

Table 3-2: CSA-W database effort summary.....3-22

Table 3-3: SSA-W mapplet requirements3-23

Table 3-4: SSA-W database effort summary.....3-23

Table 3-5: CSA-C mapplet requirements3-24

Table 3-6: CSA-C database effort summary.....3-25

Table 3-7: CSA-C database effort summary with fewer lanes3-25

Table 3-8: FCW mapplet requirements.....3-26

Table 3-9: FCW-W database effort summary.....3-26

Table 3-10: LFA mapplet requirements3-27

Table 3-11: LFA database effort summary.....3-28

Table 3-12: TSA-W mapplet requirements3-28

Table 3-13: TSA-W database effort summary.....3-29

Table 3-14: SSA-C mapplet requirements.....3-29

Table 3-15: Relative Mapplet Set Effort Multipliers by Application3-30

Table 3-16: Road type distribution metrics3-32

Table 3-17: Application to road type correspondence.....3-32

Table of Contents

Table 3-18: Database efforts by application considering target road types.....	3-33
Table 3-19: Composite database efforts by application considering target road types	3-33
Table 3-20: Road-type categories and lane miles.....	3-35
Table 4-1: PAPS positioning accuracy during GPS outages of up to 10 sec duration (as claimed by Honeywell)	4-6
Table 4-2: PAPS description.....	4-7
Table 5-1: Application distribution and potential developmental steps of safety applications ...	5-4

Executive Summary

Abstract

Digital maps, in conjunction with vehicle positioning, can enable or enhance several active safety features. For example, maps and positioning can provide information about road curvature ahead of the vehicle, information not available from other sensors. However, maps have generally been constructed for applications such as vehicle navigation, without consideration for these safety applications.

The Enhanced Digital Maps (EDMap) project was initiated in 2001 by four vehicle OEMs (DaimlerChrysler, Ford, General Motors, and Toyota), together with a commercial map database supplier (NAVTEQ), and the Federal Highway Administration and the National Highway Traffic Safety Administration. The goals of the project were:

- To identify the map accuracy and attributes (related information) required for high-benefit vehicle safety applications, and
- To understand the commercial feasibility of providing maps with this extra information.

The project began with the identification of safety-related applications, from near-term to long-term, that would benefit from or be enabled by map database improvements. The map database requirements for each application were then determined using feedback from the map database supplier with regard to data collection feasibility and database maintainability. Using the application requirements, the map database supplier constructed map databases for specified test areas. The participating automakers each evaluated and demonstrated implementations of selected driver assistance systems. The result is an assessment that will provide direction to the map suppliers in terms of the enhancements needed for future driver assistance systems, and provide a roadmap to the USDOT in terms of safety-focused systems that are enabled by enhanced map databases.

Results:

- Vehicle applications that only require information about "which road" the vehicle is on appear to be very feasible. These applications can utilize existing map structures (albeit with additional accuracy and extra information), and current vehicle positioning systems.
- Vehicle applications that require information about "which lane" the vehicle is in also appear to be viable in the next decade. These applications require "which lane" information only on selected portions of the roadway, which greatly reduces the cost. In addition, positioning systems required for "which lane" applications also appear to be commercially viable for automotive mass production, by combining planned improvements in the satellite positioning system with silicon micromachined IMUs.
- Vehicle applications that require information about "laterally where in lane" the vehicle is in do not appear to be viable in the next decade, due to their stringent vehicle positioning requirements.

The roadmap for development and deployment of vehicle safety applications that utilize enhanced digital map databases generally appears to be very promising.

Background

The EDMap team went through a process to select a set of safety applications enabled or enhanced by the use of map database derived information. The team defined a set of analysis categories by which the relative potential benefits of each application system could be compared and rated. Rating criteria included estimated safety benefit, estimated market penetration, and vehicle positioning availability. The main analysis result was a set of near-, mid-, and long-term EDMap Applications having significant safety potential:

- **Near Term (1 year after EDMap):** Curve Speed Warning, Speed Limit Advisory, Stop Sign Warning
- **Mid Term (5 years after EDMap):** Curve Speed Control, Stop Sign Control, Forward Collision Warning, Lane Following Warning, Traffic Signal Warning
- **Long Term (10+ years after EDMap):** Forward Collision Avoidance, Intersection Collision Avoidance, Lane Following Control, Automated Lateral and Longitudinal Control

For each of the applications, map database derived information, called mapplets, was defined based on the application requirements. The mapplet specifications were then used to drive the processes needed to build the EDMap databases.

Near-term applications can be supported by databases with information at the road level of granularity, the granularity of navigation-level databases today. For example, navigation and near-term databases represent geometry as the centerline of the road in the case of a two-lane road, and the centerline of each side of the road in the case of a multi-lane divided highway. The attribution for near-term databases became more definitive compared to navigation databases, but remained at the road level. For example, navigation databases store speed ranges and a range for the number of lanes to determine traversal time estimates. Near-term databases store actual speed limits and the exact number of lanes, still as road attributes. Stop sign attributes, parametric road-level curvature and other new attributes are not in today's navigation-level database, and have been added for near-term database requirements.

However, mid-term applications, such as Lane Following Warning and Forward Collision Warning, require a database with increased accuracy and information at a lane-level and even sub lane-level of granularity. For example, mid-term applications require information about the centerline and width of each lane so that position in the lane can be determined. Mid-term databases require lane centerline representation with the precision and accuracy at the decimeter level. Storing lane information not only requires road type attributes about each lane, but also requires additional attributes, such as lane striping and shoulder information, that were not required at the road level.

Application analysis in the EDMap project focused on evaluating a subset of the applications using vehicle implementations within the context of the ability of the map databases and positioning systems to support the applications. This information was used to contribute to the conclusions in this report regarding the effectiveness, deployability, and commercial viability of the selected applications over a defined future time frame. It was hypothesized that the analysis would identify mapplets having little or no impact on the effectiveness of the applications, additional mapplets to enhance the effectiveness of the applications, and new thinking regarding the required accuracy of map entity information.

Major Milestones

The EDMap team completed a major milestone of demonstrating applications utilizing near- and mid-term map databases. The following applications were demonstrated in Palo Alto in January 2004 and in Detroit in March 2004:

- Curve Speed Assistant-Warning, -Control (CSA-W and CSA-C)
- Stop Sign Assistant-Warning, -Control (SSA-W and SSA-C)
- Forward Collision Warning (FCW)
- Lane Following Assistant-Warning (LFA-W)
- Traffic Signal Assistant-Warning (TSA-W)

These are the map-aided applications that would have the significant safety potential. Additionally, these vehicles were used to evaluate the functionality of the implemented applications as a function of the database in use. The demonstrations were held on public roads. Engineering test drives were used to demonstrate the applications. No general population field testing was included.

Application Analysis

This section of the Executive Summary highlights observations and insights about the applications as implemented in EDMap with regard to map and vehicle positioning aspects. It should be noted that optimization of the application Human Machine Interface (HMI) for the various applications was outside of the scope of this project. Each application is identified as a WHATROAD, WHICHLANE, or WHEREINLANE dependent application. In increasing order of map matching accuracy, a WHATROAD application needs road-level map matching to operate; a WHICHLANE application requires map matching to a particular lane to operate, and finally a WHEREINLANE application requires map matching laterally within a lane to operate. It is noted here that the descriptions below are the result of evaluations conducted on roads that were mapped specifically for the EDMap project. While the mapped areas contain a diverse variety of road types, generalizations must be made carefully.

Curve Speed Assistant—Warning and Control (CSA-W and CSA-C)

Variants of CSA were implemented with both the road-level and lane-level maps. General Motors (GM) implemented a road-level CSA-W application while Ford implemented both a road-level CSA-W and a lane-level CSA-C application. CSA in the warning mode was evaluated as a WHATROAD application, and the control mode was evaluated as a WHICHLANE application. CSA is an application almost completely enabled by the map database and in particular by the curvature mapplet.

The GM implementation includes a Heads-Up Display (HUD) for displaying information to the driver. As a driver approaches a curve, the warning application serves in an advisory capacity and uses the HUD to display a colored icon indicating the direction of the curve ahead. While the driver approaches the curve, the warning application calculates an appropriate speed for the curve. If the vehicle is traveling faster than the appropriate speed, taking into account the driver's opportunity for braking before the start of the curve, the icon changes color as a warning to the driver, indicating the vehicle should be slowed before entering the curve. The Ford implementation of CSA-W uses a haptic seat for conveying information to the driver. As the vehicle approaches the curve, the driver is presented with vibrations from the haptic seat, depending on the vehicle's speed entering the curve. The CSA-C implementation uses the lane-level map database to determine curve speed in a manner similar to CSA-W. When enabled, the control feature behaves in a manner similar to adaptive cruise control (ACC), using the throttle and brakes to decelerate the vehicle to the curve speed in an appropriate manner for curve entry. CSA-C also can enable a curve-adjusted speed resumption after the curve.

The CSA analysis evaluated the application performance with specific attention to the curvature maplet and can be divided into two segments: curve detection and curve accuracy.

Curve detection determines whether or not a curve is represented in the map in a yes/no mental model. In other words, does the map "see" the curve or not? A set of 100 road-level database curves was analyzed for detectability, resulting in approximately 85% of the curves being detected properly. The curve detection errors comprise three main, essentially equally distributed groups:

- **Map-based application missed detection of a curve:** Occurs mostly on large radius of curvature road segments.
- **Map-matching or positioning problem causing a missed detection or false detection of a curve:** Occurs where the road-ahead branches, e.g., exit ramp, and the driver's intended route is unknown.
- **Map-based false detection of a curve:** Occurs on large radius curves; similar to the first group.

The misdetections due to curve fit noise on the large radius curves can be handled by either reclassification of the maximum detectable radius or by adjustments in the curve fitting process. The errors due to map matching are more problematic but can be addressed, in large part, by the use of routing information or lane-level maps.

The separation of the control mode as a WHICHLANE application was due to the need to have the proper preview of the upcoming road curvature. In multi-lane road configurations, the lane in which the vehicle travels can often be relied upon to provide indication of, for example, a ramp to be taken. Without lane information, the CSA-C application would likely need to be disabled when coming upon road bifurcations. CSA-W, on the other hand, does not interfere with vehicle speed, and may be more tolerant of road-split induced false alarms.

Assessing curve accuracy determines how useful the detected curves are for the CSA applications. The curvature specification for CSA was to be within 10% for warning mode and within 5% for control mode. In the delivered EDMAP databases, two classifications of curvature error were observed:

- **Link-forced errors:** Curve fits were done link-by-link and did not take into account the overall shape from link to link. The discontinuities in curvature can induce incorrect curve speed values.
- **Curve fairness errors:** The curvature values sometimes varied too much from the steady-state curve shape as the result of the curve fitting process to the collected data. The variations can cause discrepancies in curve speed values and curve start/stop location.

Remedies to the curvature out-of-spec conditions were identified and implemented, where possible. The 5% curvature requirement for CSA-C was found to be tighter than required and was relaxed to that of CSA-W. CSA-C does not need to be a lane-level application due to tighter requirements on curvature accuracy. The control version of CSA was demonstrated on road-level maps with no significant performance reduction over that of the lane-level maps except when approaching bifurcations and ramps as described above.

Other mapplets such as grade, superelevation, speed limits, and road class were found to be of secondary value to curvature, and while not required to enable CSA, may be useful for future refinements. The preceding statement can be made, given the heavy dependency on the proper preview of the upcoming vehicle path. Recommendations for map-assisted proper preview are presented in the full report.

Stop Sign Assistant—Warning and Control (SSA-W and SSA-C)

The Toyota-implemented SSA-W application employs a road-level database map with WHATROAD positioning sensors to warn and notify drivers of the presence of stop signs and stopping locations when it appears that they may drive through the posted locations without stopping. The application also warns drivers of the presence of yield signs when it appears that they may drive through a posted location without first slowing down and checking traffic conditions. In addition, the application issues an advisory when the driver passes a stop ahead sign.

The SSA-C application, also by Toyota, employs a lane-level map database with WHICHLANE positioning. In addition to warning drivers of the presence of stop signs and stopping locations, SSA-C brings the vehicle to a stop or at least reduces vehicle speed before entering the intersection when it appears that the driver may drive through the posted location without stopping. The brake control feature serves as a backup to the warning function and is designed to bring the vehicle to a complete stop once the deceleration threshold for the control function has been reached. In this regard, the SSA-C application functions in a significantly different manner than automatic braking systems. The SSA-C application provides the same functionality as the SSA-W application with regard to yield and stop ahead signs.

The SSA analysis evaluated the application performance with specific attention to stop sign, stopping location, stop ahead sign and yield sign mapplets. The analysis was segmented into mapplet detection and accuracy, and vehicle positioning accuracy and repeatability.

The mapplet detection phase of the evaluation showed there were two main modes in which detectability errors affected SSA performance:

- **Commission:** Posting mapplets on the wrong side of the road, where no signs actually existed, or facing the wrong direction.
- **Missing/Omission:** Actual signs that were not included in the database.

The errors of commission and omission were widespread in the first and second generations of both road and lane-level databases. The stop sign mapplets are the main input for SSA; therefore, detection errors have significant effect on system performance. Rectification of the commission and omission deficiencies was time-consuming; however, frequent interactions between the SSA application evaluation and map database development teams resulted in database edit process improvements and subsequent database improvements. The final delivered map database did not contain omission or commission errors on the demo routes.

Stop sign mapplet accuracy and vehicle position accuracy are closely linked. For the Palo Alto demonstration route, the mapplet position accuracy was between 14 before and 8 meters past a given location. Vehicle positioning, on the other hand, had higher variability with errors between 5 to 15 meters. Similar results were obtained for the Michigan demonstration route. The position variations reported are for the road-level map and WHATROAD positioning systems. It was discovered that because of the map matching function employed by the road-level map database and the physical positioning of the vehicle on the route, the system could adequately reduce lateral position errors and perform the warning and control functions. The longitudinal position errors did not affect the warning function as much it did the control function.

Mid-term positioning, on the other hand, was designed to perform lane-level map matching and did not perform well when vehicle positioning errors increased to the extent that lane matching was no longer accurate. The unintended consequence was that the vehicle was often declared off-road. When this condition occurred, upcoming mapplet information would no longer be available and the application would no longer be available. Thus, in order to provide effective control, a more accurate and robust position sensor is needed. This unforeseen effect could have been prevented with robust degradation from lane-level to road-level map matching. Such robust degradation capability is highly recommended for future implementations.

Also recommended for SSA is some form of forward vehicle range detection. In the event of the presence of a preceding vehicle at a stop-signed intersection, an on-board forward object sensor can provide distance information that the application could employ to determine if a warning should be issued for the approaching mapplet or for the preceding vehicle. Because this feature does not become active unless the preceding vehicle is within proximity of the approaching mapplet, this forward object warning feature is directly tied to the map database.

The original SSA specification requested mapplets for stop sign location, stopping location (white line across the road), yield sign location, stop ahead sign location, and grade. It has been concluded from the mapplet evaluation work that the stop sign and stopping location mapplets can be collapsed into a single stop sign mapplet, with the stopping location (virtual or real) as the location indicated. The stop ahead mapplet is not needed. The grade mapplet was originally intended for use in calculating required deceleration. Due to inaccurate grade information, this approach was abandoned in favor

of a constant feedback loop. However, the grade mapplet is still seen as valuable, especially in locations where the absolute value of the grade is at least 5%.

Forward Collision Warning (FCW)

GM evaluated a Forward Collision Warning (FCW) application using the lane-level map database and WHICHLANE positioning, utilizing the Honeywell positioning system. FCW uses a radar sensor that identifies potential collision targets in its field of view. Based on the range and range rate to potential collision targets, a HUD provides information to the driver indicating potential threat levels. Keys to the success of a radar-based FCW system are:

- Correct selection of in-path targets, i.e., those that are in the expected future path of the host vehicle (no missed detection), and
- Correct elimination of irrelevant targets, i.e., those not actually in the forward path of the vehicle (no false alarms).

This is accomplished by determining the intersection of the identified radar targets with the upcoming road geometry. This makes the accurate and reliable prediction of host vehicle path an important and essential component of the FCW algorithm.

Based on the radar targets and the predicted upcoming lane geometry, the target selection module selects the closest in-path target. The primary mapplet that supports the target selection module is host vehicle lane geometry estimation. The target selection module uses other mapplets to develop a valid look-ahead range by limiting upcoming path definition to an approaching stop sign, stopping location, or intersection in conjunction with vehicle speed. It uses the forward lane geometry, look-ahead range, lane width, and vehicle heading in lane for classification of radar targets as in-path or out-of-path. In addition, the target selection module uses the overhead stationary roadway structures, stationary roadside objects, and the stationary roadside barriers mapplets from map module to reduce false alarms. Finally, it provides the target IDs of closest in-path moving (CIPV) and closest in-path stationary (CIPS) radar targets to the threat assessment module.

Analysis of the FCW application is based on the ability of the mapplet information to improve classification of in-path targets and out-of-path targets, which causes false in-path classification. The effectiveness of map-aided target classification has been estimated by evaluating the map-based target selection against two other sources. The first comparison target selection algorithm is the yaw rate-based algorithm (also known as radar-only) contained in the forward-looking radar and primarily used for adaptive cruise control applications. The other comparison is the same target selection algorithm used with the map-based data but using the GM-developed post processed ground truth to define the upcoming path instead of the map.

The evaluation task is time consuming as there are hundreds of targets to classify in a typical FCW test drive. A post processed “ground truth” based evaluation scheme was developed to aid in the semi-automatic evaluation of the yaw-rate based and EDMap-based target selection schemes. Six test drives in the California and Michigan areas (total length of 45 miles) comprising a large sample size of approximately 15,000 records were analyzed to compare the target selection performance obtained using the yaw-rate based and the EDMap-based classification schemes against the post processed “ground truth” path.

The highlights of the comparison of the radar-based and the EDMap-based target selection over the six test runs are listed below. Overall, the EDMap-based target selection outperformed the yaw-rate based (radar-only) target selection by approximately 13% of all instances. A breakdown of the total analysis revealed:

- In over 82% of all instances, the EDMap-based and the yaw-rate based target selection both agreed with each other and selected the correct target (if any).
- A significant value added by maps was observed in 15% of the total cases, where the EDMap-based target selection consistently selected the correct targets and the yaw-rate based target selection either selected an incorrect target or missed a target. One primary driving scenario in which maps aid path-based target classification is in curve transitions. Yaw-rate based path estimation has proved to be very effective in predicting the proper vehicle path along sections of roads with constant curvature, straight or curved. However, during curve entry or exit scenarios, the yaw-rate based path prediction will be in error until the transition completes.
- Of the total records, very few instances (approximately 1.2%) of both EDMap-based and yaw-rate based target selection being incorrect were noted.
- A detrimental effect of using maps for target selection was observed in only 2% of the total records when the yaw-rate based method selected the correct target while EDMap-based target selection either selected an incorrect target or missed a target. These instances are attributed to the cases of inaccurate path geometry, or when the distance to the target was over 120 meters EDMap limits look-ahead range to 120 meters, while the yaw-rate based and the ground truth-based target selection are at times able to classify targets at ranges greater than 120 meters.
- The mean error in lane geometry was determined to be 0.25 meter and 0.75 meter for the preview distances of 60 meters and 120 meters respectively from the host vehicle.
- 28% of all the examined records are within 0.5 meter accuracy specification for a preview distance of 60 meters, while 16% are within the same specification for a preview distance of 120 meters.
- 65% of all the examined records show less than half a lane width of error for a preview distance of 60 meters, while 47% show the same level of error for a preview distance of 120 meters.

Overall, the accuracy of the various mapplets was not uniform in quality throughout the databases. It was found that whenever the accuracy requirements were met, the original requirements specified for the lane geometry, road grade, and intersection locations were found to be adequate and useful to the FCW application. Mapplets containing stationary roadside barriers (e.g., guard rails) and stationary overhead object information, when present (many cases of mapplet omissions were recorded), were helpful in correlating stationary objects with stationary objects tracked by the radar. It may be possible to attach the roadside mapplets to the road-level database even though the mapplets were originally specified for lane-level maps. The requirements on other mapplets, namely road surface type and road class, can be relaxed to conform to their definitions present in the current production navigation databases. Several of the originally specified mapplets namely lane width, road condition, and stationary roadside objects did not offer any

tangible benefits to the FCW application and can be deleted from future databases built to aid this application.

Traffic Signal Assistant—Warning (TSA-W)

The goal for the TSA, implemented and evaluated by DaimlerChrysler, is to avoid red light violations by warning a driver if the vehicle approaches a red light without any indication of stopping.

The application is based on a lane-level map with WHICHLANE positioning, utilizing the Honeywell Prototype Automotive Positioning System (PAPS) sensor for positioning in addition to the traffic signal position and stopping location mapplets reported by the map. The warning portion is very similar to a stop sign warning once a red light is detected. For the TSA, the stop warning algorithm is configured such that if the driver does not slow down and a deceleration of at least 0.4 Gs is needed to stop the vehicle at the stopping location after a reaction time of 1.0 second, an audible warning (“*Stop, red light!*”) is issued to the driver. The main advantage of the map is in aiding a vision system to detect the signal indication relevant to the lane in which the vehicle is traveling.

The detection of signal heads and the corresponding indication does not pose a major challenge to a vision system, and can be done very reliably with a stand-alone vision system. Signals at complex intersections, however, represent a challenge since it is not necessarily obvious which signal head controls the lane the vehicle is in, especially when the road approaching an intersection is curved. As demonstrated, the Traffic Signal Assistant successfully manages to identify the correct signal indication in complex intersections by focusing on the signal locations and status reported by the map. The search boxes are 3 meters wide and extend from 1.5 meters above the horizon to 7 meters above the horizon. The projection of the search boxes takes into account the vehicle GPS position, the signal head GPS position, vehicle heading, and camera offset from the GPS receiver.

Limiting the search to the search boxes also permits an increase in vision system sensitivity. While a stand-alone vision system is generally unable to detect the signals until the vehicle is less than 50 meters from the intersection, the TSA generally detects a signal indication when the vehicle is 50 meters to 80 meters from the intersection. Under good conditions, a signal might even be detected as early as 120 meters from the intersection.

The TSA analysis evaluated the application performance with specific attention to the mapplets involving traffic signal position and stopping location. The analysis was segmented into mapplet detection and accuracy, and vehicle positioning accuracy.

The traffic signal position mapplet detection phase of the evaluation showed that there were two main modes in which detectability errors affected TSA performance:

- **Commission:** Assigning the signal to an incorrect lane.
- **Omission:** Signal head location absent in the database.

The errors of commission and omission for traffic signal location had a similar effect on TSA performance as did analogous detection errors for the SSA. The effect was less severe than SSA, as the vision system is the primary sensor for TSA. However, if the position was off by a lane, the wrong traffic signal may create an inappropriate warning response.

The accuracy of the traffic signal location mapplet was difficult to evaluate. Ground truth is difficult to obtain in a busy intersection, and the positioning system cannot be located directly under many signal heads. What was measured was the position of the traffic signals relative to the vision system search boxes at 50 and 80 meters from the stopping location at an intersection. The signal indication needs to be known at about 80 meters from the stopping location in order to generate a reliable warning at speeds higher than 35 mph, and at least 50 meters from the stopping location at speeds lower than 35 mph. Using this approach, a rough estimate of the signal location error could be determined. Using 34 signal-controlled intersections (133 signal heads) on the Palo Alto test route, only 40% of the signal heads were located in the vision system search boxes at a distance of 80 meters from the intersection. At 14 signal-controlled intersections on the Michigan evaluation route, 47% of the signal heads (out of a total of 35) were located in the vision system search boxes at 80 meters from the intersection.

The measured accuracy of 34 stopping location instances found 34% of all instances were less than 3 meters in error and 66% less than 5 meters in error. There was a bias toward position location into the intersection; however, the cause was not identified. A stopping location less than 3 meters from the ground truth would generally give the driver a good warning and enough time to comfortably stop the vehicle. A reported stopping location of between 3 to 5 meters ahead of the intersection would give the driver the impression of an early warning, and a stopping location of more than 5 meters ahead of the intersection will cause a premature warning. On the other hand, a stopping location of between 3 to 5 meters beyond the actual stop line would give the driver a slightly late warning, and heavy braking would be needed to stop the vehicle at the stop line. A stopping location of more than 5 meters behind the intersection would give the driver an unacceptably late warning, if any.

Vehicle positioning performance in this WHICHLANE context determines whether or not adequate lane placement can be established. While an error of one-half lane width should be tolerable, error stack-up of vehicle positioning and map lane centers limited the vehicle position error tolerance to approximately 1 meter. When the estimated position error exceeded 1 meter, the TSA system was disabled.

It may be possible to add traffic signal location and stopping location mapplets to road-level maps to gain limited TSA functionality for signaled intersections where there are no lane specific signals. The potential benefit to the vision system has not been evaluated.

Lane Following Assistant—Warning (LFA-W)

The Lane Following Assistant is demonstrated in warning mode and is commonly also referred to as Lane Departure Warning (LDW). The goal in this mode is to warn a driver when the vehicle is leaving the lane. In the DaimlerChrysler version of LFA-W, the application is a combination of a vision lane tracker and a Map/GPS system. The map portion of the application is based on a lane-level map with WHEREINLANE positioning, using the Honeywell PAPS positioning unit. Under normal circumstances, the two systems (vision and Map/GPS) can operate simultaneously and will deliver very similar output variables, the most important being offset from the lane center, lane curvature and geometry ahead, and lane width. Hence, there is a high potential for sensor fusion, which allows an overall system to choose the best available sensor (vision or Map/GPS) to determine the vehicle's position in the lane and predicted travel path.

The fused LFA-W phase of the evaluation did not prove successful. The reasons for this outcome fall into two basic categories:

- Insufficient map accuracy
- Unreliable high precision GPS (this includes differential correction coverage)

The lane-level accuracy needed to accomplish effective LFA-W was specified to be 30 cm in the map database, with no more than 20 cm vehicle positioning error. The error stack-up (combined map error and position error) is 50 cm, and is at the upper boundary of combined error that can still yield useful lateral lane position information.

The lane-level maps for Palo Alto and Michigan were evaluated by comparison with the computer vision lane tracker. The lane tracker offsets helped isolate the vehicle position errors from errors in the map database. Using the lane tracker, the lane accuracy performance was found to be 30 cm and better approximately 30% of the time in the Palo Alto test route, and approximately 40% for the Michigan test route. The Michigan lane data was reviewed and a process deficiency was identified. Re-collection and editing of a portion of the Michigan route increased the 30 cm and better performance to 80%. Errors in other portions in the Michigan database remain at the 30 cm (or better) accuracy level for less than 50% of the time.

The vision-based lane tracker performs very well. It detects the lane edges very reliably and is able to infer the vehicle position within the lane most of the time. This is true even for lanes that have Botz dot lane markings on both sides (California test area). The Map/GPS system can reliably place the vehicle in the correct lane; however, it does a poor job of determining the vehicle's position within that lane, rendering it virtually useless in a lane departure warning capacity.

It is important to note here that map-based LFA-W is the most demanding on both mapping techniques as well as vehicle positioning. While the feature can be demonstrated successfully in selected scenarios, robust map-based LFA-W is clearly pushing up against implementation limitations.

Since data fusion was not possible, the EDMap evaluation proceeded to operate the two systems independently, except for the small amount of information that the vision-based system received from the map. The mapplets that were evaluated as an aid to the vision system are curvature and lane adjacency—both being lane-level mapplets used for WHICHLANE positioning. The use of curvature was to provide hints to the vision system when the road transitioned from straight to curved, and vice versa. The curvature mapplet was too noisy in the transition instances and was deemed to be unhelpful as a lane tracker aid. The lane adjacency information for lane markings type was found to have a minor impact on lane tracking, where the intent was to aid the camera by providing information such as solid or dashed lines, or Botz dots. The adjacency mapplet indicating what kind of lane is on either side of the current vehicle lane did prove to be useful information for LFA-W as it was successfully used to influence the warning severity if the lane edge being departed was the outer lane, i.e., road edge. If the road edge is a broad shoulder, crossing it is probably less dangerous than inadvertently drifting into another traffic lane. But if there is a barrier or drop-off, the road edge might be *more* dangerous.

Vehicle Positioning Analysis

Vehicle positioning was analyzed as a variable. The NTBox with GPS and code DGPS and a Honeywell Inertial Navigation System (INS) were used for the application demonstrations. The NTbox with GPS and code DGPS were used for the near-term (WHATROAD) applications; the Honeywell INS was used for the mid-term (WHICHLANE and WHEREINLANE) applications. Honeywell was used as a measure for the road-level data.

From the application perspective, it became apparent from the demonstrations in California and Detroit that positioning is a major limiting factor in the deployment of the lane-level applications. In tree-covered areas, especially in California, systems often lost GPS signals and the INS in use drifted significantly in a very short amount of time, making the application essentially unusable. One concept considered, based on the demonstration information, was to have the positioning gracefully degrade, i.e., when lane-level map matching cannot occur, default to road-level matching for as long as possible, essentially setting up three levels of performance: lane-level matched, degrading to road-level, degrading to no-map matching. Preliminary analysis of lane matching algorithms to accommodate this graceful degradation, although technically feasible, would be a significant modification to the existing implementation—in essence, a rewrite beyond the scope of this project.

Initially, only two levels of questions were asked of positioning: "What road am I on and in which direction am I headed?" (road-level positioning), and "Where in the lane am I?" (lane-level positioning). An intermediate level of useful functionality—"Which lane am I in?" is very useful positioning information for the curve speed warning/control applications. These applications work well when the system knows which road a driver will take when faced with a choice, such as an exit ramp. The exit ramp may have a curve, where warning or control would be beneficial, whereas on a through road it would not be beneficial. The system has no way to determine which path the vehicle will follow. One possible approach to mitigate the path question is to use the route calculated by an in-vehicle navigation system to make assumptions about the intended vehicle path. This would be useful in vehicles with navigation systems, with a calculated route.

WHICHLANE applications are also faced with the prospect of securing an OEM affordable source of positioning accuracy in the 1 to 0.5 meter range to locate a vehicle in the correct lane. WHICHLANE positioning capability could come from a class of receiver that exists today known as a code based narrow correlator working in conjunction with code differential corrections. Accuracy, especially in the range for WHICHLANE positioning, is not a significant goal for high volume GPS receiver manufacturers. The result is WHICHLANE receivers are currently cost prohibitive for automotive applications. Although currently prohibitive, cost will likely be significantly reduced by increased high volume interest and subsequent production orders of WHICHLANE receivers.

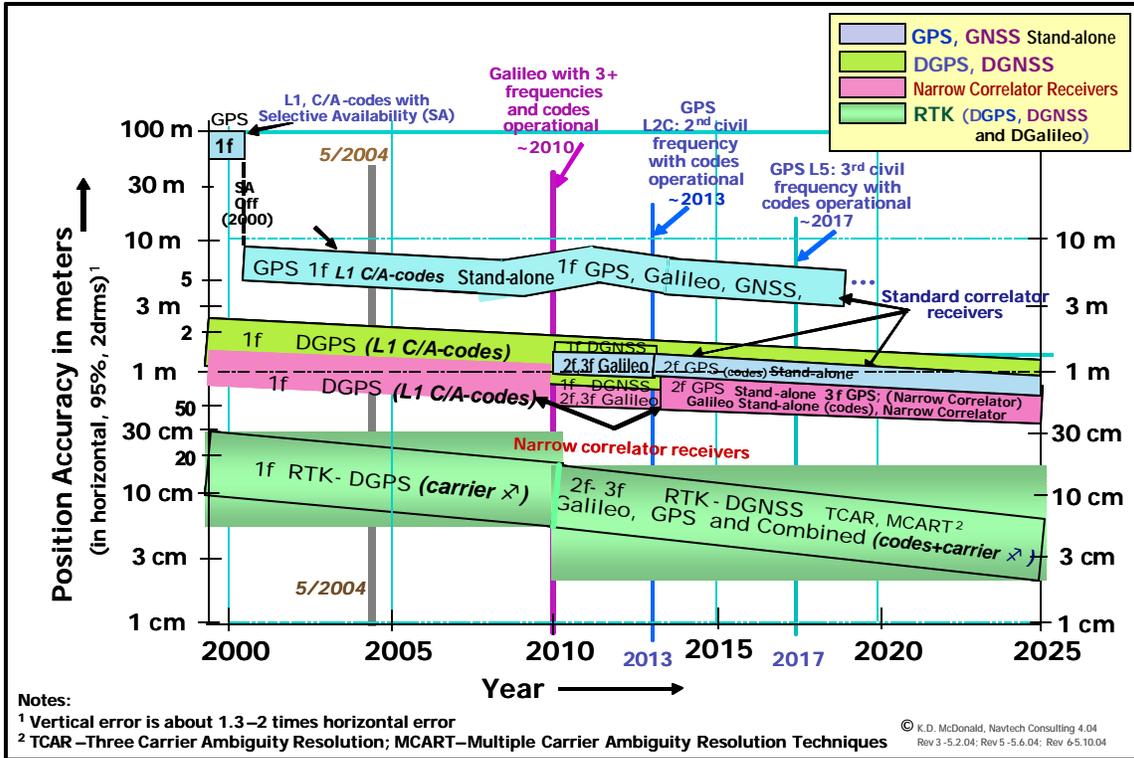


Figure 1: Likely Global Navigation Satellite System (GNSS) capability timeline

Figure 1 shows a reasonably comprehensive, albeit information packed, timeline of positioning capability for WHATROAD, WHICHLANE, and WHEREINLANE applications. WHATROAD application requirements are met by current 5-10 meter GPS units in vehicle navigation systems today. The center grouping of positioning in the 0.7-1.2 meter range shows the opportunities to achieve WHICHLANE applications. The lower grouping in the 0.03-0.2 meter range can provide WHEREINLANE capability; however, such capability is expected to be OEM affordable in the long term.

The acceptable vehicle positioning errors are based on a total error budget that combines the expected error of the map database with vehicle positioning error. For WHICHLANE applications, the total error budget is 1.5 meters (half of a 3.0-meter lane width). For WHEREINLANE applications, the total error budget is 0.5 meters (based on LDW requirements).

Table 1: Error budget for WHICHLANE and WHEREINLANE applications

	Total Error Budget (map + vehicle) [meters 2sigma]	Map Error [meters 2sigma]	Vehicle Positioning Error [meters 2sigma]
WHICHLANE	1.5	0.5	1.0
WHEREINLANE	0.5	0.2	0.3

Map Database Analysis

The database analysis was approached from several perspectives. The first perspective was the assessment from the application point of view, describing the effects of the delivered mapplets on the application operation, as well as database quality. This application assessment of delivered mapplets was covered above in the Application Analysis section. The database quality assessment is covered in this section. Secondly, the maps were analyzed for commercial feasibility with an emphasis on potential rollout time frames as well as the overall relative effort required to create maps that satisfy individual and grouped (WhatRoad, WhichLane, WhereInLane) application requirements. The results of these analyses are also discussed in this section.

Map Quality

The accuracy and precision of the EDMap databases were determined through a sampling approach since 100% recollection of the databases was not feasible due to time and cost. Sampling is a method used in statistics to alleviate the problem of re-collecting an entire population of data. Often, it is impractical or even impossible to collect all relevant data. An accepted practice is to sample a proportion of the population.

An optimal sampling size of 35 was chosen in order to minimize data collection time and cost while at the same time ensuring the sample size yields statistically significant results. This sample has been proven to yield a reasonable level of uncertainty. A sample size of 35 was determined to be the minimum sample needed to yield statistically significant results. This sample size reduces the standard error in the binomial distribution to +/- 2-3% at a 97% confidence interval. This sampling size dictated 35 sample routes to be driven for each subgroup, each of which contained at least 35 road sections. Refer to Section 3.5, *Quality Metrics* and Appendix E Quality Assessment Report for further details.

Using the sample size of 35, the results show a very small difference in the standard error of the sampled routes, indicating that this sample size is sufficient for the EDMap databases to yield statistically significant results.

An assessment of the quality of each database was developed by measuring the quality of a small, but statistically representative, set of road segments in each database and using that subset to reflect the characteristics of the entire population of road segments. Quality analysis databases, superior in quality to the original EDMap databases, were created for each subset through the use of higher accuracy data collection equipment and/or the collection of multiple passes per segment. The quality analysis databases were then used to measure the accuracy of the mapplets in each EDMap database.

The geometric quality of the databases was determined by measuring the relative accuracy of the sampled segments. Relative accuracy was calculated by using an Iterative Closest Point (ICP) algorithm to align a segment in the EDMap database with the corresponding segment in the quality analysis database and then computing the spatial deviations between the segments. The relative accuracy results are summarized as follows. For the mid-term databases, approximately 96% of the geometry had maximum deviation values of less than 2 meters, 93% less than 1.5 meters, 85% less than 1 meter, and 51% less than 30 cm. For the near-term databases, approximately 85% of the geometry had maximum deviation values of less than 2 meters, 80% less than 1.5 meters, and 72% less than 1 meter.

In addition to the geometry, the accuracy of EDMap road attributes was examined and statistics were generated for link (e.g., number of lanes, speed limit, and surface type) and point attributes (e.g., stop signs, yield signs, and stopping locations). Approximately 83% of link attributes were

coded correctly and 82% of point attributes were coded correctly. For point attributes that were coded correctly, the positional accuracy of each attribute was then determined. As an example, of the stop signs that were coded correctly, 90% were placed within 10 meters of the correct position, 64% within 5 meters, and 10% within one meter. The details of the accuracy of each attribute were determined and are presented in Section 3.5 *Quality Metrics*.

The quality metrics presented above were determined from a database created prior to validations and other process improvements, which were added in the creation of the map databases used for the application demonstrations. These database process validations and improvements are required to bring the database to an acceptable level of application usability.

It is also critical that the application have some understanding of whether the database area specifically in use at any particular time meets the specification or not, as well as how the application behaves in areas where the map data does not meet the EDMap specification. Development of a Quality Mapplet was outside of the scope of this project and is suggested as possible future work below. The behavior of each application in areas where the map data does not meet the EDMap specification is covered in the detailed report section for each application.

Map Database Commercial Feasibility

The map database commercial feasibility can be viewed from two perspectives: lead time and effort.

Database Lead Time

There are some practical limitations to how fast the defined databases could be rolled out. One aspect of these limitations is the time to reach a production environment. Another is the time to actually produce the databases once the effort is underway.

The road-level EDMap databases are an extension of the current commercially available navigation databases. As such, the production environment is also an extension of the current production environment for navigation databases. Thus, it is estimated that it would require only about 6 months to get to a production-level environment for these databases, given a production-level navigation database capability.

Looking to the time to produce these databases, some estimates can be made based on collection metrics from navigation database experience and experience gained through the EDMap project.

The number of miles to drive for collection can be estimated as follows:

- 5,000,000 road miles exist in the US for all road types
- 2 drive miles are required for each road mile (2 directions)

There are, therefore, about 10,000,000 miles to drive to collect this data. The capacity to collect this data can be estimated as follows:

- 200 collection vehicles (based on current database provider fleet)
- 200 miles driving per day (based on EDMap experience)
- 240 working days per year

Therefore, the lead time to collect the data would be:

$$10,000,000 \div 200 \div 200 \div 240 = \sim 1 \text{ year}$$

Although this estimate only covers the collection time, editing could be done in parallel as collected data is delivered.

As described previously, a lane-level database is a step change in complexity, effort, etc. over a road-level database. Much experience has been gained through the EDMap project. It is estimated that it would require about two years to get to a production-level environment for these databases. This effort would include the development of production-level editing tools, changes to current processes, and personnel training.

Looking to the time to produce these databases, some estimates can be made based on collection metrics from experience gained through the EDMap project.

The number of miles to drive for collection can be estimated as follows:

- 5,000,000 road miles exist in the US for all road types
- 2.2 drive miles are required for each road mile (2 directions for 2-lane roads + multiple lane roads)

There are, therefore, about 11,000,000 miles to drive to collect this data. This number is not significantly different from the determined for road-level databases. The difference in lead time is dependent on the collection fleet possible.

The capacity to collect this data can be estimated as follows:

- 20 or 200 collection vehicles (based on current database provider fleet)
- 200 miles driving per day (based on EDMap experience)
- 240 working days per year

Therefore, the lead time to collect the data would be:

$$11,000,000 \div 20 \div 200 \div 240 = \sim 10 \text{ years}$$

$$11,000,000 \div 200 \div 200 \div 240 = \sim 1 \text{ year}$$

The number of vehicles in the collection fleet is very dependent on the cost to purchase and maintain the equipment. The cost for the collection vehicle INS is currently around \$150,000 each, which severely increases the equipment cost. It is projected that this cost will approach \$15,000 in the mid-term time frame, leading to the feasibility of a 200 vehicle fleet. Note that the above fleet sizes were used for illustrative purposes only and are not based on a rigorous commercial analysis of prospective map suppliers.

Although this estimate also only covers the collection time, editing could be done in parallel as collected data is delivered.

Database Relative Effort

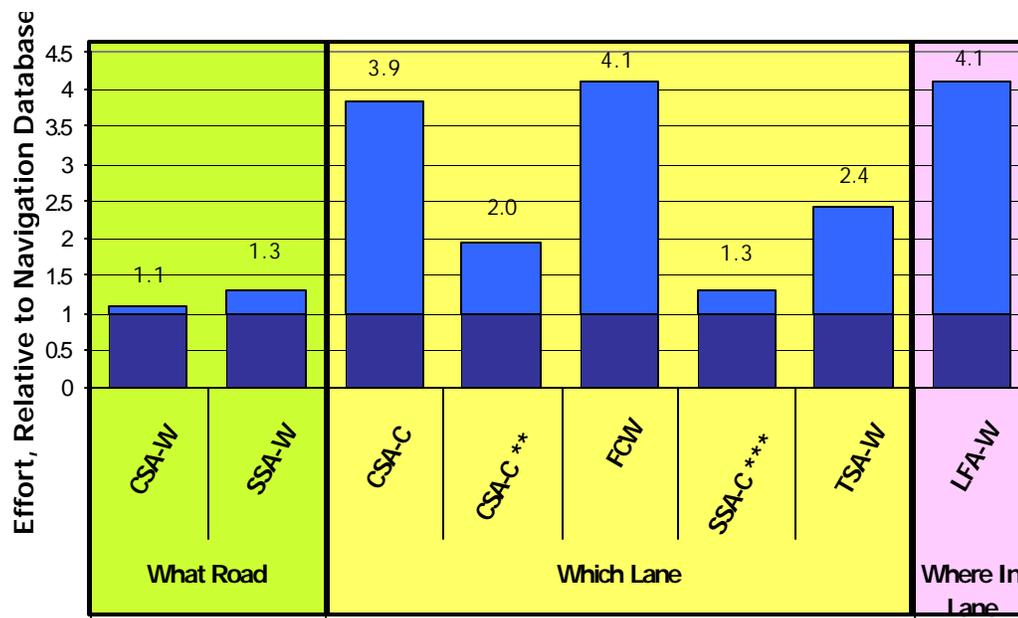
Database Relative Effort is the effort required to create an EDMap database compared to the effort required to create an existing commercial navigation-level database.

OEMs evaluated their applications based on the delivered databases. As a result, the OEMs were able to specify the minimum set of attributes and database accuracies required, by application. NAVTEQ was then able to use the specific maplet requirements for each database to estimate the relative effort associated with the database for each application.

Note that effort does not indicate price in the commercial product sense.

Each application-specific database was evaluated to estimate the effort of producing such a database in comparison to current navigation-level databases. Note that these relative effort estimates all assume a starting assumption of no database. Previous analysis estimated the effort to create a road-level database that encompassed all of the applications' road-level requirements in one database. Likewise, an estimate was done previously for the composite (all application) lane-level database. Previous analysis estimated that a composite road-level database would require approximately 25% more effort to build than to build the current commercially available navigation-level databases. A composite lane-level database would require approximately six to eight times the effort to create the current navigation-level databases compared to the effort to build the current commercially available navigation-level databases. Additional experience over the past six months has resulted in updated estimates of 35% and five to seven times the effort for road-level and lane-level databases, respectively. The 35% estimate includes the SSA estimates, which increased to a 30% differential due to the conclusion that roads would need to be driven in each direction to effectively capture stopping location data, essentially nearly doubling the collection effort for stopping locations.

The following chart summarizes the applications by type (WHATROAD, WHICHLANE, or WHEREINLANE) and by the relative effort multiplier.



** Limited to road bifurcations

*** Application control mode functioning on Road Level database

Figure 2: Applications by type and relative effort multiplier

Analysis of each application-specific database resulted in several discrete categories of database creation effort. The Curve Speed Assistant-Warning application, which requires a road-level database, demands a database requiring approximately 10% more effort than current navigation-level databases. The Stop Sign Assistant-Warning application, also requires a road-level database, and demands a database which results in a 30% effort increase over current navigation-level databases.

Additionally, an analysis of Curve Speed Assistant was done considering the inclusion of lane-level data only when approaching bifurcations or ramps. This would reduce the lane data editing effort to about one-third of the editing for providing lane-level information everywhere and would reduce the effort to create such a database to about two (1.95) times the effort of a navigation-level database.

The functionality of the Stop Sign Assistant application was not appreciably enhanced with the use of lane-level data, and thus road-level estimates from SSA-W are also valid for SSA-C.

Breaking down relative effort by application provides an interesting slice through the range of road and lane-level maps. It is now possible to "pick and choose" an application based on relative effort.

Effort Mitigation

The effort increase was identified as a deployment limiting factor for a number of the target applications. Each application was then analyzed recognizing that its potential effectiveness is not uniformly distributed across all road types in a database. One method of effort mitigation is to apply applications to the road types that would potentially provide the most safety benefit.

A summary of application effort mitigation follows:

- **Stop Sign Assistant:** Interstate highways and freeways could be excluded
- **Curve Speed Assistant:** Low speed residential streets could be removed from the CSA map coverage area, and potentially cover 86% of target crashes.
- **Forward Collision Warning:** Low speed residential streets could be removed from the CSA map coverage area, and potentially cover 92% of target crashes.
- **Traffic Signal Warning:** Interstate highways and freeways could be excluded
- **Lane Departure Warning:** Include only freeways and controlled access highways. Also can include only road classes having speed ranges greater than 40 mph, which could potentially cover 70% of target crashes.

Therefore some deployment savings may be realizable by considering which portion of the road network would be most applicable for those applications where cost/effort were identified as deployment constraints, while not significantly compromising the potential safety benefit of the application. One logical way to segment the database for the purpose of evaluating applicable database scope is to define several road types, the applicability of each road type to each application, and the prevalence of that road type relative to the complete database based on road segments, which are approximately proportional to miles.

The following road classifications were derived from those commonly used for navigation database segmentation, for which database profile data is available. These definitions prove to be useful in the segmentation of the safety application database as well.

- **Interstate highways and other freeways:** These are roads with very few, if any speed changes. Access to the road is controlled. These roads allow for high volume, maximum-speed traffic movement between and through major metropolitan areas.
- **Other freeways, typically state highways:** These are roads with some speed changes that allow for high volume, high-speed traffic movement. These roads are used to channel traffic to the higher throughput roads for travel between and through cities in the shortest amount of time.
- **Arterial Roads:** These roads connect roads at the next highest throughput category and provide a high volume of traffic movement, although at a lower level of mobility than the above category roads.
- **Neighborhood Connecting Roads:** These are subdivision roads, which provide for a high volume of traffic movement at moderate speeds between neighborhoods. These roads connect with higher throughput roads to collect and distribute traffic between neighborhoods.
- **Neighborhood Roads:** These are side street roads whose volume and traffic movement are below the level of any of the above throughput categories.

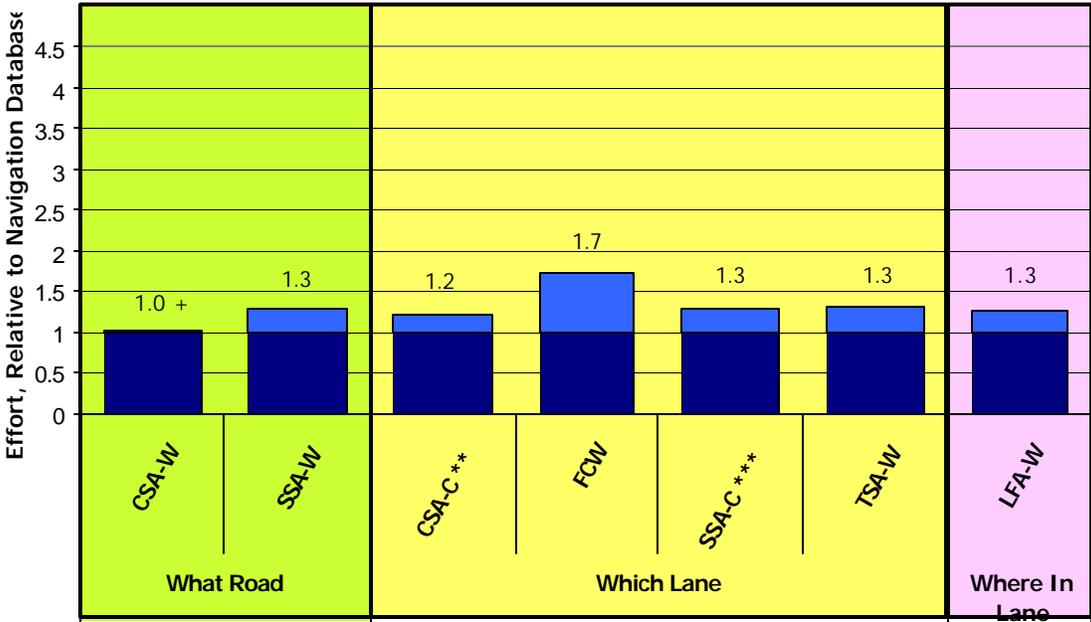
The following table shows the distribution of the above-defined road levels across the United States, the potentially most effective road types for each application, and the resultant proportion of the database applicable for that potential effectiveness.

Table 2: Road-type distribution and application usage metrics

Distribution of roads in USA	Road Type	Application						
		CSA-W	CSA-C	SSA-W	SSA-C	FCW	LDW*	TSA
1.0%	Interstate Highways							
1.6%	State Highways							
7.0%	Arterial Streets							
12.9%	Neighborhood Connecting Roads							
77.5%	Neighborhood Roads							
	Total coverage required	23%	23%	90%	90%	23%	8%	22%

* Roads with speed limit > 40 mph

Effort mitigation considering road type for deployment yields the results shown in Figure 3.

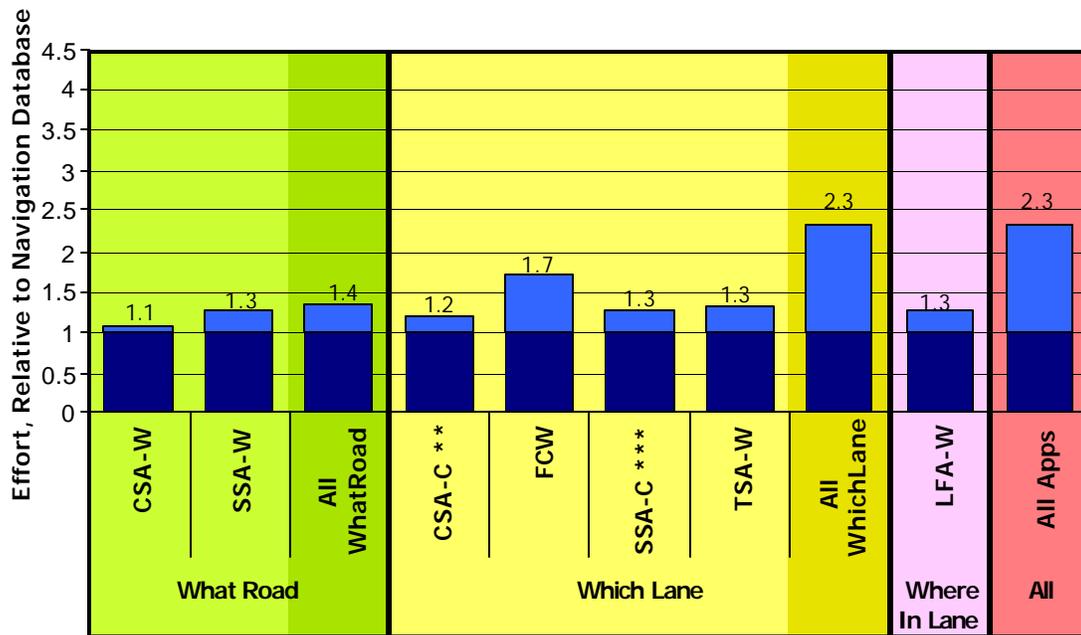


**Limited to road bifurcations
 ***Application control mode functioning on Road Level database

Figure 3: Database efforts by application considering target road types

Deployed roads saving can only be applied to the additional effort over navigation databases. All estimates assume the presence of a navigation-level database on all roads as a base. Therefore, for example, with FCW having an effort multiplier of 4.10 and being deployed on 23% of the roads, the net effort would be $1 + ((4.10 - 1) * .23) = 1.7$.

Additional insight into a composite database, taking into account the effort mitigations described above, can now be derived, keeping in mind that some attribute requirements, such as Lane Geometry and Lane Curvature, are shared among applications. A composite database effort view for each type of application then yields the results shown in Figure 4.



**Limited to road bifurcations

***Application control mode functioning on Road Level database

Figure 4: Composite database efforts by application considering target road types

Database Commercialization Perspective

The analysis shows that road-level databases are likely feasible on a commercial basis, using an extension of equipment and processes already in use for navigation-level databases. In addition, lane-level databases appear to be more restricted by rollout time frame than by effort, after the effort mitigations are applied. In this context, rollout time frame refers to the time required to build production quality tools needed for collection and database creation, and to deliver a commercial database containing new attributes. It should be pointed out that the effort mitigations applied may also have some rollout timeline benefit as well. The timeline benefits, however, can not be estimated without further investigation. Further opportunities for investigation in this area can be focused in two areas: 1) analyze the lane-level requirements to determine which lane-level mapplets could be assigned at a road-level basis and 2) investigate the creation of databases specifically to support WhichLane applications. For example, guardrails are defined as a lane-level attribute. Guardrails could be assigned to the road-level database. Questions remain, beyond the scope of this current project, related to how the applications would perform with this modified road-level database.

Final Conclusions

EDMap project tasks were designed to focus on safety related applications, and to use the application requirements to drive improvements needed in the map database. From this perspective, the EDMap project can be viewed in two distinct phases: a “paper” phase and a “practice” phase. The paper phase was a research and planning phase conducted to determine application and map requirements based primarily on analysis and past experience. This paper phase established the initial conditions for the practice phase where map and application requirements were put into practice. The implementation evaluations in many respects confirmed the initial requirements. In several key areas, however, the practice phase helped stratify and prioritize the must-have and optional requirements. This selection process came about as the result of careful development iterations of both the map database as well as the applications themselves.

With that in mind, the EDMap project summary is captured by the following points:

- Application and maplet evaluations led to key optimizations
- Vehicle positioning capability is in the critical path for deployment
- The demonstrated EDMap applications provide a good basis for a roadmap of map-enabled safety applications

Key Optimizations

The EDMap paper phase produced a map effort estimate that, especially for the lane-level map, projected effort multipliers significantly beyond feasible limits (5 to 7 times that of the current navigation intent map database). However, review of the maplets with respect to content and extent has shown potential for significant effort reduction compared to estimates made earlier in EDMap.

Map content optimizations were achieved through a variety of means, and the result was that maplets were culled from the original requirements list and map creation effort was reduced. Map extent optimizations were also made toward the end of the evaluation process. Each application developer reviewed the respective accident exposure, and determined the effect on potential application safety benefits if road coverage was reduced. For applications needing residential streets, the map extent effect on optimization was minimal due to the high percentage of residential roads in the United States. For applications not needing residential streets, the effect was quite significant.

Vehicle Positioning

At the beginning of EDMap, the prevailing view on vehicle positioning capability was that vehicle positioning was adequately addressed by either existing or planned GPS capability or improvements. As the project progressed, the view was partially confirmed for the near-term (road-level) applications, where the road-level map effort multipliers were very manageable, and the accuracy and reliability of production-grade vehicle positioning sensors (navigation-level GPS and dead reckoning sensors) in conjunction with map matching proved to be acceptable in application evaluations.

The view for high accuracy positioning, capable of determining lateral offset in a lane for Lane Departure Warning, became more pessimistic during the project. The positioning system did not maintain reliable lane offset information due to affordability constraints placed on the system. While this was a less than desirable outcome, the effort multiplier for lane-level maps was high

enough that the impracticability of lane offset positioning was essentially moot—both were in long range time frame.

However, map optimizations and the emergence of WHICHLANE applications places the ability to position the vehicle in the correct lane in the critical path for WHICHLANE application deployment. It is understood that IMU developments are needed in MEMS gyros to deal with short-term outages, yet baseline WHICHLANE positioning needs to come from GNSS (either differential GPS or Galileo). Accuracy, especially in the range for WHICHLANE positioning, is not a significant goal for high volume GPS receiver manufacturers. The result is that these WHICHLANE receivers are currently cost prohibitive for automotive applications. Although currently prohibitive, cost will likely be significantly reduced by increased high-volume interest and subsequent production orders of WHICHLANE receivers.

Applications as a Guide

The use of EDMap applications enabled specific and targeted evaluations that in turn motivated map optimizations and exposed vehicle positioning deployment issues. The applications were a guide to the overall project, and while it could be argued that there are map database uses other than safety that will impact database deployment, one can reasonably argue that restricted focus on safety applications helped keep the EDMap project degrees of freedom from exceeding manageable evaluation limits.

The evaluated EDMap applications exercise the full range of map and vehicle positioning complexity as shown in Table 3. The timeline is implicit in a top-down direction where WHATROAD applications are most imminent, WHICHLANE follows, in no particular order, with better vehicle positioning, and finally WHEREINLANE is longer term where reliance on accurate vehicle positioning as well as map accuracy is most demanding.

Commercial feasibility potential was dramatically increased by the maplet optimization approaches taken where the maplet content and road map extent allowed the map effort multipliers to be reduced from unreasonably high levels. Positioning accuracy capability will continue to be a key commercialization factor for deployment of WHICHLANE applications, and especially WHEREINLANE applications.

Table 3: Application distribution and potential developmental steps of safety applications

Application Type	Application	Maplet Effort	Positioning Accuracy			
			10-3m	3-1m	1-0.3m	<0.3m
WhatRoad	SSA-W	1.3X				
	CSA-W	1.1X				
WhichLane	SSA-C	1.3X				
	TSA-W	1.3X				
	FCW	1.7X				
	CSA-C	1.2X				
WhereInLane	LDW	1.3X				

Future Topics

The EDMap project made significant accomplishments toward the production advancement of applications and map databases for vehicle safety. While there is no direct follow-on project planned for EDMap, there are topic areas that can be investigated.

Hybrid Map Database

EDMap developed and tested road and lane-level map databases. As one of the project results, a map database containing both road-level and sections of lane-level was identified as a potential evolutionary step from a road-level database to enable applications that only need lanes in areas of road bifurcations, e.g., CSA control and FCW. In such an example, the map would contain road-level geometry and attribution on the majority of road segments, and would switch to the lane-level map representation near bifurcations or other areas where lane specific information is needed by an application (a WHICHLANE application).

While the prospects of such a hybrid map appear promising, hybrid maps containing both road- and lane-level were not built and evaluated in EDMap, therefore, such a step is warranted. The reason to consider such a step is that evaluation in the context of an application will likely uncover design challenges previously not addressed. An example for a hybrid map would be the transitions between road-level to lane-level and back to road-level. Map collection and editing techniques will need to ensure smooth transition, and applications will need a maplet interface capable of mixed level map information.

Vehicle Positioning to Support WHICHLANE Applications

WHICHLANE applications emerged as a grouping of applications requiring vehicle positioning accurate enough to locate the vehicle in the correct lane in the map database. To meet the vehicle positioning requirements, the lateral positioning error should be less than 1 m in order to reliably support correct lane placement. As described earlier in the report, EDMap vehicle positioning systems were targeted at the WHATROAD and WHEREINLANE levels. No specific testing was performed with a vehicle positioning system with affordable potential specifically at the WHICHLANE level.

A possible future project topic could be to determine vehicle positioning options to achieve reliable and cost effective WHICHLANE positioning. There are alternatives to achieving vehicle positioning to less than 1.0 meter, and each alternative has capabilities and constraints that should be analyzed theoretically, and then tested with actual equipment.

Stopping Location Collection and Maintenance Using Probe Data

Creating reliable stopping location mapplet data for the SSA and TSA applications was problematic in EDMap. The implemented countermeasures for stopping location mapplet validation are not bulletproof. Errors of commission and omission, as well as accuracy error, cannot all be captured by the proposed validations. Additionally, database maintenance, particularly when a new stop sign is installed, currently is addressed by either customer feedback or local field office surveys. And finally, the stopping mapplet emerged as one of the more “expensive” mapplets from the map effort perspective. All these factors point toward improvements in the stopping location mapplet collection and maintenance.

Data from probe vehicles is understood to have the potential to be used in many aspects of map database collection and maintenance. A good opportunity exists to improve the stopping location mapplet using probe data. Time-spaced probe vehicle positions could be clustered to identify likely stopping locations to address mapplet omission and commission errors, thereby improving the reliability of this mapplet in the delivered map database. Using probe data for the specific purpose of stopping location reliability improvements could be a well defined and clearly containable future work topic.

Map Database Update

The aspect of map database maintenance related to the detection of change, primarily via the potential use of probe data has been addressed in this project and suggested as a topic for future work. Current and projected wireless data transfer capabilities have also been reported in the appendices. The investigation and prototyping of delivering fresh map data to the vehicle could be a beneficial future work topic.

Quality Indicator Mapplet

About halfway through the EDMap project a mapplet, called the Quality Indicator (or Quality) mapplet, was proposed. It was a new mapplet, not part of the original mapplet set that was intended to capture map performance to specification at a road segment level of granularity. In other words, each road segment would have a mapplet that contained information describing just how good the database was for a particular road segment. The quality mapplet was envisioned to provide data such as geometry standard deviations or anticipated error for a given class of point attribute. The idea was to then use the quality mapplet in the vehicle application to provide a level of operational reliability.

Currently, and in EDMap as well, quality assessments are/were made based on a composite database area. In practice, some road segments would be very accurate, and others not so accurate, but the overall amalgamation could be within tolerance.

EDMap made some progress with relative accuracy metrics and assessments of accuracy for certain point attributes based on the collection methods. This was a good start, and can enable, for example, an application to create an error model for stopping location based on the collection method assessment. The database quality “polling” technique performed for EDMap is also a good approach to include statistical rigor to the quality assessment, and could be further deployed in the quality maplet construct to sampled areas. More work would need to be done to determine the level of granularity, in terms of area, road, or road section that provides the best benefit with respect to improved application performance reliability.

1 Introduction

1.1 Report Layout

This introduction provides project background as well as task results that can be viewed as preparation and support for the main goal of database evaluation for the EDMap applications. The following chapters provide results of the application and map database evaluations.

Chapter 2 presents the EDMap application results from the perspective of how the application performed with regard to the mapplets as well as vehicle positioning. Chapter 3 provides an analysis and discussion of the mapplets and the map databases built. Vehicle positioning performance was a key performance factor, a factor as important as the mapplets themselves. Therefore, Chapter 4 presents information on vehicle positioning.

Chapters 2, 3, and 4 are interdependent and interrelated, as mapplet collection and edit processes are motivated by application needs, and vehicle positioning capabilities are key enablers, or in some cases, limiting factors in application performance.

Chapter 5 pulls the map and application efforts together and draws conclusions and recommendations based on the mapplets the applications required, as well as what it took to deliver the maps at the needed quality levels.

There are several appendices in this report. The most significant is the independent map-database quality assessment. Other appendices include descriptions of selected software tools developed to analyze data and details regarding the demonstration vehicles and positioning systems employed in the project.

1.2 Overall EDMap Plan

The Enhanced Digital Map Project (EDMap) was a three-year effort launched in April 2001 to develop a range of digital map database enhancements that enable or improve the performance of driver assistance systems currently under development or consideration by U. S. automakers. The project began with identification of safety-related applications, from near-term (within three years after completion of the EDMap project) to long-term (at least ten years after project completion), that would benefit from or be enabled by map database improvements. The map database requirements for each application were determined using feedback from the map database supplier with regard to data collection feasibility and database maintainability. Using the application requirements, the map database supplier constructed map databases for specified test areas, and participating automakers each employed these map databases to develop, demonstrate, and evaluate the performance of selected driver assistance systems. The resulting assessment provides direction to map suppliers in terms of the enhancements needed for future driver assistance systems, and provides a roadmap to the USDOT in terms of safety-focused systems that are enabled by enhanced map databases.

1.3 Motivation and Background

According to the year 2000 NHTSA statistics, 41,821 persons were killed in an estimated 6,394,000 police reported traffic crashes [1]. In 1994, the economic impact of reported and unreported crashes was estimated at \$150 billion [1]. To address the impact of these staggering statistics, appropriate crash avoidance countermeasures that aid in reducing the fatality rate, as well as costs, related to vehicle crashes must be developed.

Vehicle-based solutions to the major collision categories identified by NHTSA crash data analyses (rear-end, roadway departure, lane change/merge, intersection, and driver impairment) can be best addressed by considering a suite of sensing capability with each sensor providing redundant or complementary information. In particular, radar ranging, computer-vision lane tracking, and map database driven positioning can form a sensor triad for improved driver assistance systems.

Driver assistance systems are currently being developed and deployed as the result of improvements in computer vision and radar¹. It is understood that while computer vision and radar provide critical enabling technology for systems such as road departure warning and forward collision warning, they are unable to complete the perception and contextual understanding of the driving scenario. To increase the overall reliability of a crash avoidance system the use of any and all forms of additional sensory information should be explored. One such source of potential information can be derived from a map database. A digital map database and the associated navigation system are important to the development of Advanced Driver Assistance Systems (ADAS). Digital map navigation provides a connection between the vehicle and the roadway infrastructure that is not possible with other ADAS sensors such as radar or computer vision. While digital map navigation does not obviate the need for other ADAS sensors, it serves as a necessary component in the development of future driver assistance systems.

The goals of EDMap were to provide effective direction to map suppliers regarding enhancements needed to enable future driver assistance systems and to establish the feasibility of generating and maintaining these enhancements. The goals extend to vehicle manufacturers through which a coordination of map database structure is enabled. The overarching goal of map suppliers and vehicle manufacturers is to provide the USDOT a roadmap of safety-focused applications enabled or enhanced by a digital map database.

1.3.1 Map Database as a Sensor

Digital map databases used in turn-by-turn vehicle navigation systems are designed to route the user through a representation of the road network to the desired destination. Map database support for such a navigation system places emphasis on a database of destinations as well as sufficient representation of navigable roads. The road representation includes attributes such as one-way roads, average traffic speed, and road classification, e.g., highway, in order to enable route calculation. When the map database is linked with vehicle positioning using dead reckoning and the Global Positioning System (GPS), the resulting navigation system is capable of forming a route to the desired destination, and subsequently tracking the vehicle as it proceeds along the route.

¹ Emergency brake assist (radar) and lane departure warning (computer vision) features are to be available in the 2005 model year from Toyota and Nissan, respectively.

The navigation system and its map database can also be thought of as a localization sensor for applications beyond the scope of route guidance. Working as a localization sensor, the navigation system could be used to determine the upcoming road shape for an advanced feature such as curve speed warning or headlight aiming. The sensor uses dead reckoning and GPS to locate vehicle position with respect to the digital map. The map database is then queried to gather geometric information of the road ahead. The upcoming road geometry information could then go to driver assistance systems such as headlight aiming, to make the appropriate beam modifications. The degree to which such advanced features could function, however, would depend on the quality of individual sensors. For example, it has been reported [2, 3] that an accurate localization sensor may be capable of supporting a road departure warning application.

Figure 1-1 depicts representative map database information *possible* in a road network where road geometry information, road attribute information (e.g., speed limits, bridge locations, etc.), and intersection information are shown. Each set of information contained in the map has the potential for multiple uses in vehicular applications. For example:

- Lane geometry information can be used for radar target tracking as well as to aid a lane change system.
- Lane width, edge coordinates, grade and bank angle, can be used for road departure warning and lane keeping applications.
- Elevation and bank angle can be of use to a system that provides curve speed assistance.
- Preview of upcoming curvature information can be used to provide curve speed assistance and radar target tracking.
- Speed limit information can be used for a wide variety of features including speed advisory.
- Bridge information can be used for radar target classification as well as a prediction for slippery overpass conditions.
- Stop sign and traffic signal locations can indicate intersection stop spots and can be used to develop stop sign and stop light assistant applications.
- Turn lanes, turn restrictions, and other intersection geometry information can add additional safety benefit to navigation systems.

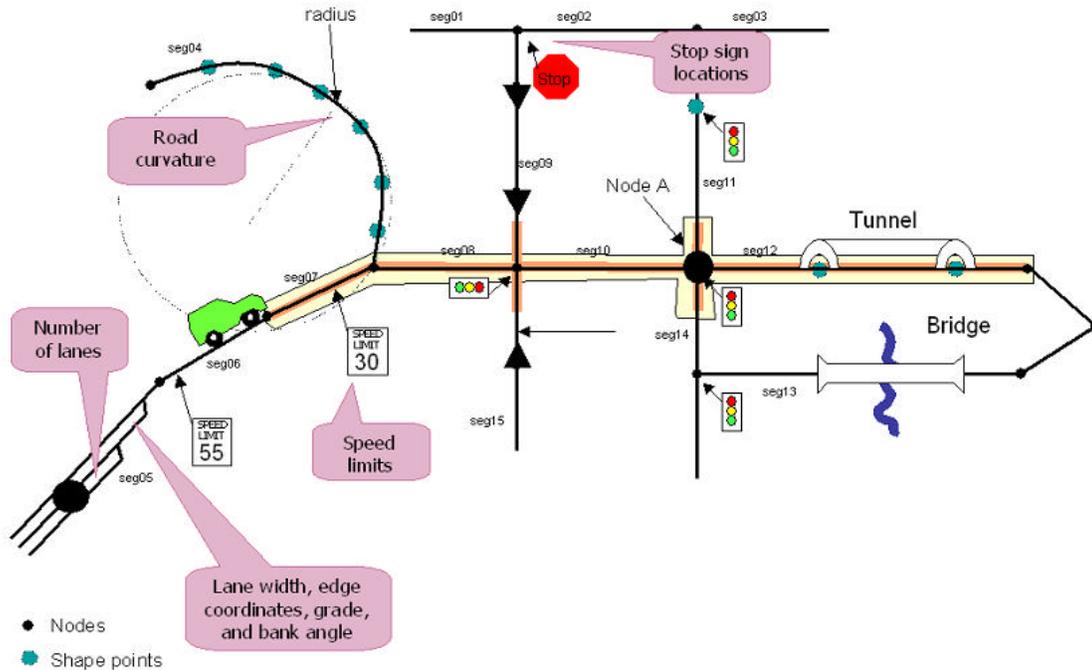


Figure 1-1 Road network with enhanced map attributes

1.3.2 Current Map Database and Vehicle Positioning Capability

Current map database accuracy is at a level where curve speed warning may be realized with a limited degree of functionality. Map database accuracy is in the range of 5 to 15 m, and vehicle positioning accuracy is approximately equal that of the map database. Information regarding map coverage and attributes can be found in Appendix B, Section B.5, *Assessment of Existing Database Capabilities and Application Needs*.

Map database accuracy can be improved to sub-meter accuracy using existing technologies, however, there are several challenges to enhancing map databases for driver assistance applications. Advances in road database representation are needed to define road geometry efficiently and accurately. The road representation attributes in current map databases do not generally include lane width, number of lanes, actual speed limit, elevation, or superelevation information². The EDMAP project examined many of these aspects and proposes potential solutions to the challenges.

Today's vehicle positioning accuracy of 5 to 10 m can be improved to 3 to 5 m using code-based Differential GPS (DGPS) and fairly common DGPS capable equipment. Code-based DGPS positioning accuracy can be further improved using more expensive receivers, and improved to sub-meter accuracy using carrier phase DGPS. The latter DGPS equipment is currently cost prohibitive for production applications; however, the price/performance trends are favorable in the 5 to 10 year horizon. The key infrastructure elements required for this option are the differential base station system and the differential corrections communication network.

² NAVTEQ is delivering (2004) speed limit and number of lane information to select U.S. and European regions.

1.3.3 Navigation System Availability

Access to current map database content (and future map content) for ADAS applications depends on the availability of an onboard vehicle navigation system. Such access is obvious from a technical standpoint; however, navigation system availability in the U.S. is not yet widespread. In 2002, navigation system market penetration was 0.7% for light vehicles 5 years and younger, with an installation rate of 1.9% for new vehicles. The average OEM price was \$1500, but with a volume decreasing price gradient [4].

1.4 Tasks and Results Summary

The nine main tasks in the statement of work are summarized below. These tasks are presented in pictogram form showing the relationship between the tasks as well as the basic distribution of work in Figure 1-2. The vehicle manufacturing participants had primary emphasis in Tasks 1, 2, 3, and 6 as these tasks are related to vehicle aspects of the project. NAVTEQ had primary emphasis on Tasks 4 and 5, which involved the map database. OEMs and NAVTEQ worked together on Map Evaluation, Task 7. Also shown is Task 8, conducted with an early project onset component (8a), and an end-of-project view (8b). Task 9 comprises the documentation of the results of this project and provides recommendations.

Figure 1-2 also shows the interactive nature of the EDMap project between the OEMs and NAVTEQ. For example, there is considerable interaction between Tasks 2 and 4 as application requirements are transferred to map database attribute and accuracy needs. The interactions work both ways, as feedback from the map database work aids in further refining application capabilities and/or requirements.

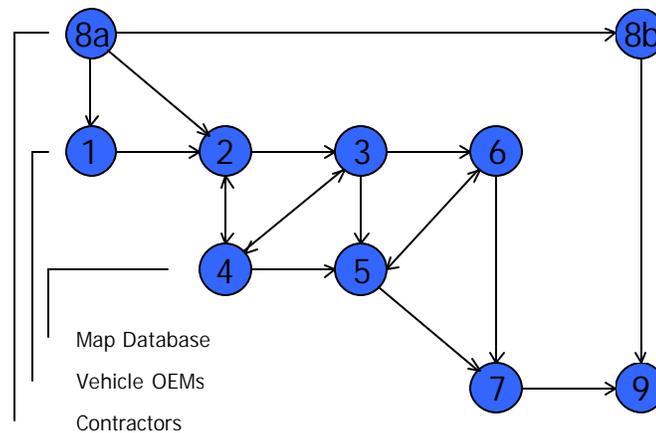


Figure 1-2: EDMap work tasks

The remainder of this chapter details the EDMap task process and presents selected portions of task results. The intent is to paint a broad view of the scope of work, and to cover common work material that supports the entire project. In some cases, e.g., application ranking done in Task 1, the results are discussed only in this section with supporting material contained in appendices. The major work tasks, e.g., Task 7, are briefly covered in this section and followed with a dedicated chapter later in the report. The reader is asked to keep in mind that this task overview is presented in a chronological manner to show information “as it was learned”, therefore, there will

be instances where conclusions drawn from early-on task work are revised in later tasks as more conclusive information was discovered.

1.4.1 Task 1 – Identification of Intelligent Vehicle Applications Enabled by Mapping Technology

The objectives of this task were:

- Build a list of applications that may benefit or be enabled by an enhanced digital map.
- Select a subset of applications that can guide database-attribute requirements. Applications should:
 - Form stepping stones of map improvements
 - Show potential safety benefits

The EDMap team identified 61 safety-related applications that could be either enabled or enhanced by map database-derived information. For each application, functional descriptions and requirements were developed. The list of requirements was used to define a group of map-derived information—*mapplets*—that support the applications. See Appendix A, Section A.1, *Applications and Mapplets* for a listing.

The team then defined a set of analysis categories by which the potential benefits of each application system could be compared. Each application system was rated with respect to the analysis categories. The three main categories were:

- Estimated effectiveness with respect statistics related to loss metrics
- Estimated deployment time frame and market penetration
- Position accuracy and communication needs

All of the applications, evaluation category ratings, and crash statistics were then put into a relational database paradigm. The database structure was designed so that database queries could be constructed to view the data from several perspectives. The EDMap Applications Database was a key development of Task 1, and served as an effective data-checking, data-mining, and decision-aiding tool. Details of the database approach used can be found in Appendix A, Section A.2, *Database Formation and Structure*.

Database analysis helped form the view that application systems were best rated by considering the statistics related to a crash loss metric called Functional Years Lost from the General Motors 44 Crashes report [4]. The time frame in which the applications could potentially be introduced into the fleet was handled by market penetration and deployment time frame estimates, and the estimated availability of positioning and communication technologies required by the application at a reasonable cost. Other analysis category views were also considered. Functional Years Lost from the 44 Crashes report may not be correct in the absolute sense, but is correct in a directional sense.

The main analysis result was a set of near-, mid-, and long-term applications having significant potential with respect to functional years saved (Table 1-1). The set of near-, mid-, and long-term application systems, in addition to spanning a range of time, also provide good crash category coverage in both freeway and non-freeway scenarios. Details of the application ranking can be found in Appendix A, Section A.3, *Application Ranking*.

Table 1-1: High safety potential applications using maps

(W = warning, C = control)

Near-term 2004-2006	Mid-term 2007-2011	Long-term 2012-2016
Curve Speed Assistant (W)	Forward Collision Warning/Avoidance (W)	Lateral and Longitudinal Control (C)
Stop Sign Assistant (W)	Traffic Signal Assistant (W)	Intersection Collision Warning/Avoidance (C)
Speed Limit Assistant (W)	Lane Following Assistant (W)	Forward Collision Warning/Avoidance (C)
	Curve Speed Assistant (C)	Lane Following Assistant (C)
	Stop Sign Assistant (C)	

It is important to state that the EDMap benefits analysis conducted in Task 1 was for the purpose of rating the relative potential of map-enabled application systems. The analysis considers incremental improvements that the map could provide for active safety systems that rely on a different primary sensor, as well as those that are enabled by a map, i.e., the map database is the primary sensor. It is also important to keep in mind that the application time frames were essentially “initial conditions” for EDMap, and, as will be seen later in the report, there were adjustments to potential application time frames.

1.4.2 Task 2 – Determination of Application Attribute Requirements

The objectives of this task were:

- For each application, determine the following for different performance levels:
 - Map accuracy/reliability requirements
 - Map attributes
 - Positioning system accuracy
- Generate feedback with respect to the effort required to collect suitable map data
- Finalize attribute requirements

In Task 2, the goal was to use the EDMap applications to drive map accuracy and attribute requirements. Map database-derived information, called *mapplets*, has been defined and specified based on EDMap application needs. The mapplet requirements were determined by an engineering analysis for each application, and then grouped relative to the near-, mid-, and long-term time frames. Mapplet definitions for the EDMap applications can be found in Appendix B, Section B.2, *Description of Mapplets*, and the detailed information regarding the analysis performed on the applications in Table 1-1 can be found in Appendix B, Section B.3, *Detailed Mapplet and Vehicle Positioning Requirements*. The approach of motivating mapplet requirements from applications identified in Task 1 as having strong safety potential supports an overall EDMap project goal of providing focused direction to map suppliers in terms of the map content required for future driver assistance systems. A summary of mapplet and vehicle positioning requirements is provided in Appendix B, Section B.4, *Summary of Map Database and Vehicle Positioning Requirements*.

Time frame based maplet grouping showed that the near-term map database represents an evolutionary step from today's navigation-based map. Required accuracy improvements are both feasible with regard to the map structure as well as mapping methods. Inclusion of near-term maplets, such as speed limit and stop signs, is feasible with some data collection already underway. For example, navigation and near-term databases represent geometry as the centerline of the road in the case of a two-lane road and the centerline of each side of the road in the case of a multi-lane divided highway. The attribution for near-term databases became more definitive compared to navigation databases, but remained at the road level. For example, navigation databases store speed ranges and a range for the number of lanes to determine traversal time estimates. Near-term databases store actual speed limits and the exact number of lanes, still as road attributes. Stop sign attributes are not in today's navigation-level database, and have been added for near-term database requirements.

The mid- and long-term maplet groupings point toward a significant change from the near-term database. Mid-term applications such as Lane Following Warning and Forward Collision Warning require a database with increased accuracy and information at a lane-level of granularity. For example, mid-term applications require information about the centerline and width of each lane so that position in the lane can be determined. Mid-term databases require lane centerline representation with the precision and accuracy at the decimeter level. Storing lane information not only requires road type attributes about each lane, but also requires additional attributes, such as lane striping and shoulder information that were not required at the road-level

Mid-term applications make use of vehicle positioning capability that is expected to be able to achieve sub-meter accuracy in the 2007 to 2011 time frame (see Task 8 for assumption substantiation). Sub-meter positioning accuracy enables applications such as the Lane Keeping Assistant. The effect on the maplet requirements to support mid-term applications is to mandate lane-level representation of roads in the map database. Current map database road geometry will require restructuring to contain a set of adjacent lane geometries sharing some information, such as edges or travel speed, but at the same time having unique information, such as width or lane stripe type. Data collection requirements are also increased.

The long-term maplet grouping is very similar to the mid-term maplet set. Required maplets are essentially the same, with the difference being increased accuracy specifications needed by control applications.

EDMap application maplet requirements provided a basis for attribute collection delivered in the near-term database. The mid-term maplet requirements were deemed within the spectrum of technical feasibility, but further investigation was recognized as being necessary to reduce uncertainties in such areas as data collection scalability and lane-level modeling. Further investigations, particularly for lane-level maps, were conducted as part of Tasks 4 and 5. Long-term maplets will follow developments from the mid-term investigation. A summary of maplet and vehicle positioning requirements is provided in Appendix B, Section B.4, *Summary of Map Database and Vehicle Positioning Requirements*.

1.4.3 Task 3 – Definition of Final Safety Demonstration

The objectives of this task were:

- Identify the applications each OEM will demonstrate so that, on the whole, a range of applications using various levels of map functionality is shown
- Define test site areas
- Define potential mapping techniques to be used, e.g., survey vehicles, road maintenance vehicles, and probe vehicles
- Define project team demonstrations in the two test areas

The capability of developing and using future EDMap databases was demonstrated in two test sites: one located in southeast Michigan and the other in the Palo Alto California region. Maps of the EDMap test site areas can be found in Appendix B, Section B.7, *Demonstration Test Sites*. The test sites were selected based on the applications to be demonstrated as well as the database collection tools appropriate for the specified mapplets. Thus, the mapplets called out in Task 2 were key components in the process of site selection and collection tools (see Task 4 for collection tool summary).

Vehicle OEMs selected a suite of applications from the set of EDMap applications (Table 1-1) to demonstrate in the test site areas. From the near-term EDMap applications, Curve Speed Warning and Stop Sign Warning were selected, and from the mid-term Curve Speed Control, Forward Collision Warning, Lane Following Warning, Stop Light Warning, and Stop Sign Control were chosen. There were no long-term applications selected for demonstration. This fact should be viewed as a positive sign that OEM interests are in applications that have potential to provide results sooner rather than later.

Table 1-2: Demonstration applications selected
(selected applications shaded) (W = warning, C = control)

Near-term 2004-2006	Mid-term 2007-2011	Long-term 2012-2016
Curve Speed Assistant (W)	Forward Collision Warning/Avoidance (W)	Lateral and Longitudinal Control (C)
Stop Sign Assistant (W)	Traffic Signal Assistant (W)	Intersection Collision Warning/Avoidance (C)
Speed Limit Assistant (W)	Lane Following Assistant (W)	Forward Collision Warning/Avoidance (C)
	Curve Speed Assistant (C)	Lane Following Assistant (C)
	Stop Sign Assistant (C)	

1.4.4 Task 4 – Data Collection and Maintainability

The objectives of this task were:

- Perform an analysis of the relative value of each mapping method
- Perform analysis of database structures for road geometry and make recommendations
- Provide collection and maintainability metrics for map database construction
- Deliver database access tools for applications

The approach taken for Task 4 was to analyze each step of the database creation process, shown in the following diagram, from the perspective of creating near- and mid-term databases and to determine the most cost effective and scalable means for the execution of each process step. The main steps are input selection, collection techniques, processing, and final data delivery to the applications.

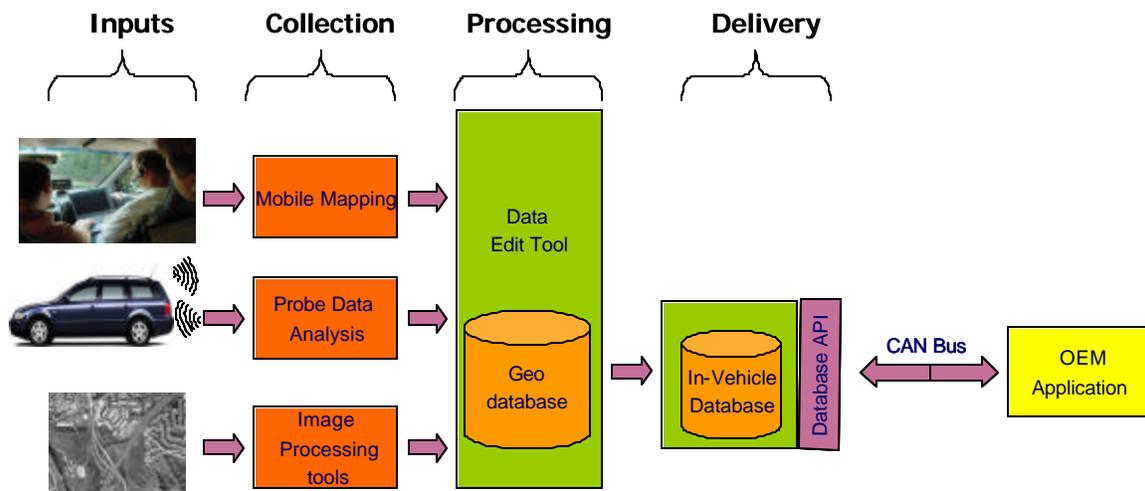


Figure 1-3: Task 4 approach

The effort to produce the safety-purposed near- and mid-term databases at each process step was then measured relative to the effort to produce today's commercially available navigation-purposed databases to gain an initial perspective of the relative costs to build databases to support the identified safety applications.

Input and collection candidates were categorized as Mobile Mapping, Probe Data, and Remote Sensing. Mobile Mapping was characterized by the use of vehicles specially equipped with DGPS and positioning sensors, along with a trained analyst operating a mobile mapping workstation. Probe Data refers to the use of passive sensors and recording devices on consumer/fleet vehicles. Data collection does not require interaction with the driver nor operation by trained personnel. Remote Sensing is used to describe any number of image sources from satellite or aerial sources, such as photography, LIDAR, radar, etc.

Evaluation of the input and collection candidates resulted in the selection of mobile mapping vehicles for both near and mid-term databases. Remote sensing was not chosen for accuracy, timing and cost reasons. A summary of evaluated remote sensing techniques is provided in Appendix C, Section C.3, *Comparison of Remote Sensing Technologies*. The distribution within each pie chart in Figure 1-4 reflects the proportion of collection, processing, and distribution for

navigation, near-term, and mid-term efforts on an ongoing basis. The effort multipliers represent an estimate to include all mapplets for the near- or mid-term for the entire U.S. map navigation database, making the estimate a full build-out effort representation. The cumulative results of Task 4 indicated that the operating effort to collect, process, and distribute near-term databases as an extension of navigation databases was estimated at about 25% more effort than the creation of navigation-level databases, primarily using mobile mapping techniques currently applied for the production of navigation databases.

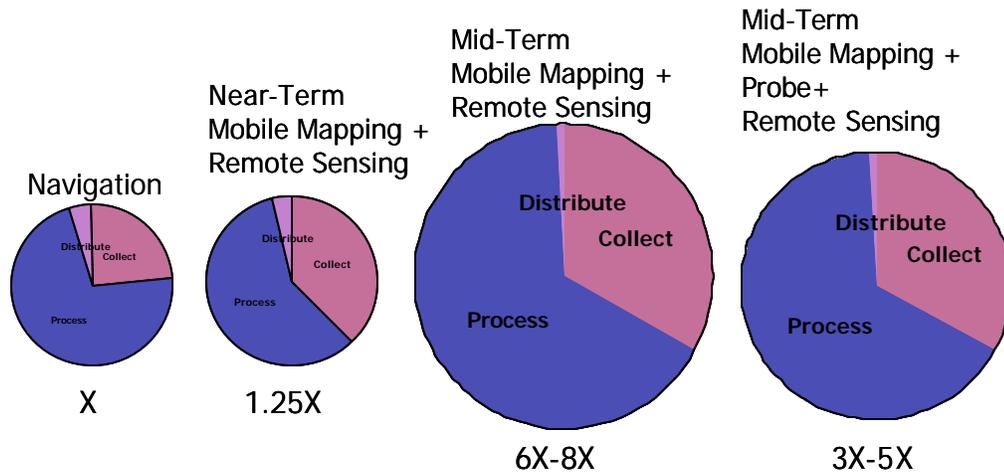


Figure 1-4: Proportion of collection, processing, and distribution for navigation, near-term and mid-term efforts

However, moving to lane-level databases represents a step increase in the database complexity and accuracy requirements, which are directly reflected in the relative effort to create these databases. A new data model and new representations for road curvature were developed to accommodate mid-term database requirements. New processes had to be developed and prototyped for mid-term database production, as well as the development of new skills for the personnel executing the process.

Using mobile mapping as the primary method for collecting mid-term data, the corresponding effort to process and edit the collected mid-term data represents 6 to 8 times the effort of creating today's navigation-level databases. This increase in effort is characterized by 8 to 10 times the data collection and 5 to 6 times the data processing effort compared to navigation-level databases.

Investigation into the use of probe data for the collection and processing of mid-term data shows the use of probe vehicles may reduce the future cost of producing mid-term databases. Rough estimates indicate that the use of probe data may decrease the cost of mid-term databases to 3 to 5 times the effort of navigation databases. The reduction in effort could potentially come from a 20 to 50% decrease in the mid-term mobile mapping collection effort and a 25 to 40% decrease in the mid-term processing effort.

The fixed costs, primarily equipment, for the three database levels (navigation-, near-, and mid-term) were also compared. The analyses indicate that the fixed costs for the near-term are about 50% higher than for navigation databases. However, the high cost of mobile mapping equipment for the mid-term increases the mid-term equipment costs to 50 times the cost of the navigation-level equipment. The cost of the probe equipment tested was between \$200 and \$1,000 per vehicle.

There remain a number of technical challenges associated with the deployment of probe data, such as collecting, storing, and moving large amounts of probe data. In addition, several non-technical issues, such as privacy and deployment cost, will influence the adoption rate of probe technology.

The foregoing effort analyses were based on an initial pass of creating near- and mid-term databases to support all near- and mid-term applications. During Task 7, two important refinements will be made as the databases are evaluated with the applications. First, evaluation of the applications may result in relaxed database requirements or the identification of a singularly costly attribute or geometric parameter. It is also likely that not all attributes are required at the same level of precision everywhere. For example, if the safety application is designed to prevent specific accident situations that occur primarily on rural roads, full attribution for urban roads may not be necessary or cost effective. Second, an analysis of the map information by each application will lead to more specific information about the cost to support each application separately, and may identify applications that are more viable than others.

A discussion of map maintainability issues is provided in Appendix C, Section C.5, *Maintainability*.

1.4.5 Task 5 – Test Site Mapping/NAVTEQ

The objectives of this task were:

- Perform site mapping of selected roads at the specified attribute accuracy and reliability levels
- Validate database in conjunction with an independent evaluator

The results of Task 4 had a significant impact on the mapped test sites. The techniques developed initially to perform map database editing underwent several iterations during the delivery of the near-, and especially, the mid-term databases. The iterations were tightly coupled with application evaluations in Task 7, and a significant amount of results regarding map delivery process improvements will be reported later in the body of this report.

Near- and mid-term databases were delivered for both the Michigan and California test sites. The mid-term test site areas were resized due to the difficulty of delivering lane-level databases (described in Task 4 above), however, the maps were able to support all primary application evaluation efforts.

A further discussion on the methods used to create the EDMap demo databases is provided in Appendix C, Section C.4, *Edit Tool*.

1.4.6 Task 6 – Demonstrator Vehicles

The objectives of this task were:

- Build vehicles (each OEM) to demonstrate one or more applications as defined in Task 2
- Implement applications using appropriate map database level and map access tools, with implementation details left to OEMs and overall performance shared

The primary objectives of Task 6 were to develop map-enabled safety applications and to implement the applications on test vehicles. The vehicles developed for this project are intended to evaluate the map requirements for specific applications. Each vehicle includes the following:

- Map database and database access tools
- Vehicle positioning systems agreed upon by the OEMs, of a quality at least as good as the map database to be evaluated
- Other sensors and systems as required by the demonstration application(s)
- Data acquisition hardware and software to evaluate the functionality of the application as a function of the map database in use

The vehicle application development approach was to create an architecture having two main sections as shown in Figure 1-5:

- A common component section comprising the map database, database access tools, and vehicle positioning
- An application-specific section comprising sensors and systems determined by application needs

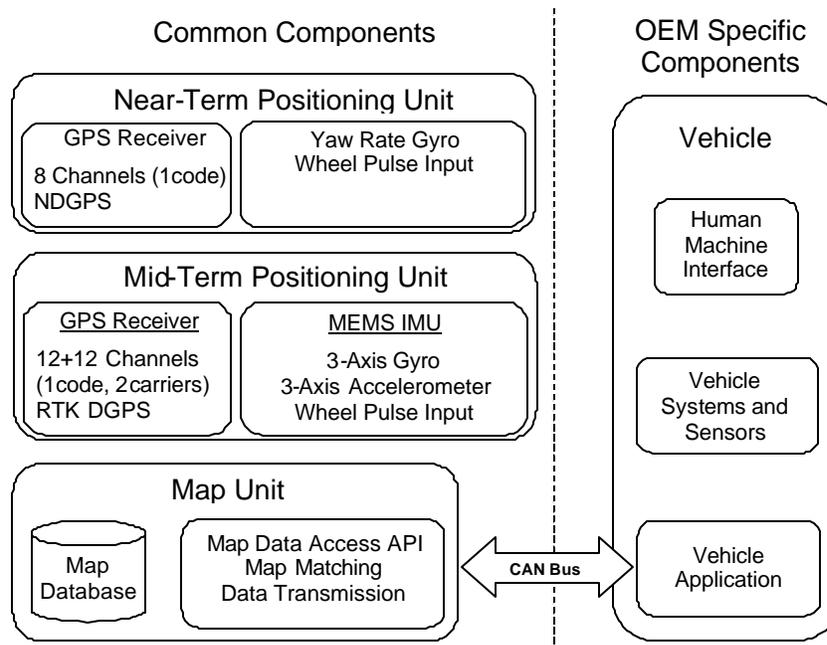


Figure 1-5: Demonstrator vehicle architecture highlighting the common components and OEM specific components

The use of many common components allows cost economies across the applications, which is sensible; moreover, the common components help reduce variation of map database and vehicle positioning use while evaluating application performance with the maps. The EDMaP team also took care to consider the potential deployment time frame of the common components in selecting the hardware.

The common architecture and components as well as particulars of each OEM vehicle can be found in the Appendix D, *OEM Test Vehicle Setups*.

1.4.7 Task 7 – Enhanced Digital Map Evaluation

The objectives of this task were:

- Determine, using demonstrator vehicles, map database quality and attributes needed to provide functionality to the application
- Consider additional attributes that would improve application performance
- Make all vehicles available for general demonstration by partnership members for evaluation
- Summarize the enabling level of each map database

Test vehicles were developed by the OEMs to implement the functionality of the applications as a function of the database in use. Using these prototype safety applications, the database for each targeted application was evaluated at both the California and Michigan test sites. The analysis of this evaluation enabled Task 7 to determine the map database quality and attributes required for each application. Engineering test drives were used to demonstrate the safety applications on public roads in California and Michigan. Key results of these evaluations are summarized in Chapter 2, *Applications and Maplet Results*.

1.4.8 Task 8 – Deployment Analysis

The objectives of this task were:

- Provide a complementary high-level study of positioning systems and communication systems
- Include GPS (accuracy, reliability, acquisition time) as well as inertial measurement units (cost, capability)
- Evaluate communication capability to support map database needs

Task 8 was divided in two parts. The first part, 8A, was conducted at the beginning of the EDMap project to provide information on expected vehicle positioning and communication capabilities, and a follow-up analysis. The second part, 8B, was conducted near project end to address advances made during the project. Independent consultants were contracted to provide the Task 8A and 8B analyses (see Appendix I).

The Honeywell Sensor and Products Division and Schaffnit Consulting provided the respective positioning and communication analyses for Task 8A. The key components of the Task 8A report were predictions of positioning and communication capabilities that would allow 30 cm level performance deemed necessary for applications such as the Lane Following Assistant. Some key findings and conclusions, (circa Jan 2002):

- GPS positioning enhancements are underway via the USDOD GPS modernization plan GPS III, and will add two additional civilian signals (L2 and L5) that should improve stand-alone receiver performance to approximately 0.2 m early in the next decade.
- Removal of Selective Availability in May 2000 has resulted in reduced DGPS network interest, especially NDGPS, the extension of the Coast Guard system to the continental U.S. The source of differential corrections appeared to be the limiting capability with regard to positioning.

- Inertial Measurement Units (IMUs) based on micro-electro-mechanical system (MEMS) technology have developed to the point where the ten-year expectation to do 30 cm positioning may be available in the five-year time frame. The MEMS IMU cost is primarily a function of production volume.
- The MEMS IMU developments make it feasible to consider lane-level tracking five years earlier than expected, provided a reliable source of differential corrections is available.
- The differential GPS corrections needed for lane-level EDMap applications require communication needs that are quite confidently not going to be met by a cellular network, which was employed during the EDMap project. It is likely that more than one communication technology will be required to meet all EDMap application needs. Potential candidates that could meet the communications needs are apparent and include digital TV or radio, 3G cellular, and especially Digital Short Range Communication (DSRC). In combination, it appears that all identified EDMap communications needs can be met.
- Predictions about the communications market are very difficult and are affected by the financial health of the country almost as much as by technological issues.

The second part of Task 8, 8B, was conducted in late 2003 and early 2004. For 8B, Navteq GPS and Schaffnit Consulting teamed up to generate the report. The 8A report was used as the initial condition for assumptions, and updates and revisions were made based on developments that had taken place since the time of the 8A report. Key findings and observations were:

- GPS enhancement pace to the satellite constellation were not happening as rapidly as expected in 8A. Result is that enhanced code capability is pushed out to 2013.
- Development progress in the EU-based Galileo proceeded rapidly since 8A, outpacing 8A expectations. Result is that overall GNSS satellite constellation will dramatically improve DOP (dilution of precision) across the United States.
- The idea of WHICHLANE emerged since 8A, and the 8B report gave consideration to reliable and cost effective positioning to determine which lane the vehicle traveled. Result was that code based receivers as well as carrier phase receivers could meet WHICHLANE requirements yet cost and reliability were unproven.
- DSRC, called out in 8A, solidified potential as a medium for map updates.
- Differential corrections remain uncoordinated with WAAS, Coast Guard DGPS and private corrections providers using a different delivery schemes.

Pertinent excerpts of both the 8A and 8B reports are in Appendix I and J.

1.4.9 Task 9 – Final Report and Recommendations

The objectives of this task were:

- Include summary results of each Task
- Provide a prediction of the types of applications that could be commercially feasible given expected map development
- Develop a timeline for deployment of maps with various levels of attribute accuracy and reliability.

1.5 References

1. NCSA, *Traffic Safety Facts 2000 - Overview*, National Center for Statistics & Analysis, NHTSA, Washington, D.C.
2. Venhovens, P., Bernasch, J., Lowenau, J., Rieker, H., Schraut, M. (1999). *The Application of Advanced Vehicle Navigation in BMW Driver Assistance Systems*, SAE Technical Paper Series, 1999-01-0490.
3. Wilson, C., Rogers, S., Weisenburger, S. (1998). *The Potential of Precision Maps in Intelligent Vehicles*, Proc. IEEE Int. Conf. on Intelligent Vehicles, Stuttgart Germany, pp. 419-422.
4. Frost and Sullivan, *North American Automotive Entertainment and Navigation Systems Market*, Report A300-18; 2003.
5. General Motors (1997). *44 crashes, v.3.0*. Warren, MI: NAO Engineering, Safety & Restraints Center, Crash Avoidance Department.

2 Application and Maplet Evaluation Results

The demonstration applications shown earlier in Table 1-2, and restated below, were evaluated in the Michigan and California EDMap test areas:

- Curve Speed Assistant Warning (CSA-W) by Ford and General Motors
- Curve Speed Assistant Control (CSA-C) by Ford
- Stop Sign Assistant Warning (SSA-W) by Toyota
- Stop Sign Assistant Control (SSA-C) by Toyota
- Forward Collision Warning (FCW) by GM
- Traffic Signal Assistant Warning (TSA-W) by DaimlerChrysler
- Lane Following Assistant Warning (LFA-W or LDW) by DaimlerChrysler

The evaluations were conducted to determine how well the applications performed with the EDMap databases with respect to delivered quality and attributes required. Sections 2.2 through 2.6 provide results for each of the five application categories evaluated.

2.1 Curve Speed Assistant

2.1.1 Introduction

Variants of Curve Speed Assistant (CSA) were implemented with both the near- and mid-term maps. General Motors implemented a near-term Curve Speed Warning application while Ford implemented both a near-term Curve Speed Warning and a mid-term Curve Speed Control application.

The General Motors implementation includes a Heads-Up Display (HUD) for displaying information to the driver. As a driver approaches a curve, the warning application serves as an advisory and uses the HUD to display one of two cyan icons indicating the direction of the curve ahead. While the driver approaches the curve, the warning application calculates an appropriate speed for the curve. If the vehicle is traveling faster than the appropriate speed, taking into account the driver's opportunity for braking before the start of the curve, the cyan icon changes color to a red icon. The red icon is the warning to the driver, indicating the vehicle should be slowed before entering the curve.

The Ford implementation of CSA Warning (CSA-W) includes a haptic seat for conveying information to the driver. The algorithm constantly computes the curvature of a determined segment of road ahead in the road-level map database. Based primarily on curvature and an acceptable curve lateral acceleration, a curve speed is calculated. As the vehicle approaches the curve, the driver is presented with motor vibrations from the haptic seat, depending on the vehicle's speed entering the curve. The CSA Control (CSA-C) implementation uses the lane-level map database to determine curve speed in a manner similar to CSA-W. When enabled, the control feature behaves in a manner similar to adaptive cruise control (ACC), using the throttle and brakes to decelerate the vehicle to the curve speed in an appropriate manner for curve entry. CSA-C also can enable a curve-adjusted speed resumption after the curve.

2.1.2 Evaluation Criteria and Test Areas

To validate the advisory feature of the Curve Speed Warning application, a tool was developed to utilize yaw rate and vehicle speed to generate an estimate for road shape and road curvature using the following equation:

$$k = \frac{\dot{f}}{v}$$

where k is the road curvature and is the inverse of curve radius, v is the vehicle speed, and \dot{f} is the change in heading, or yaw-rate, of the vehicle. The curvature tool is described further in Appendix F, *CSA Evaluation*.

Figure 2-1 and Figure 2-2 show the demonstration routes for the CSA applications in Palo Alto, California and southeast Michigan, respectively. In these figures, the freeway routes are shown in blue color and include multiple lane freeways and their associated ramps. The non-freeway routes consist primarily of single lanes in each direction with some instances of multiple lanes in each direction. The CSA demonstration and some of the application performance is based on these routes. Any other routes used in the analysis are described in subsequent sections.

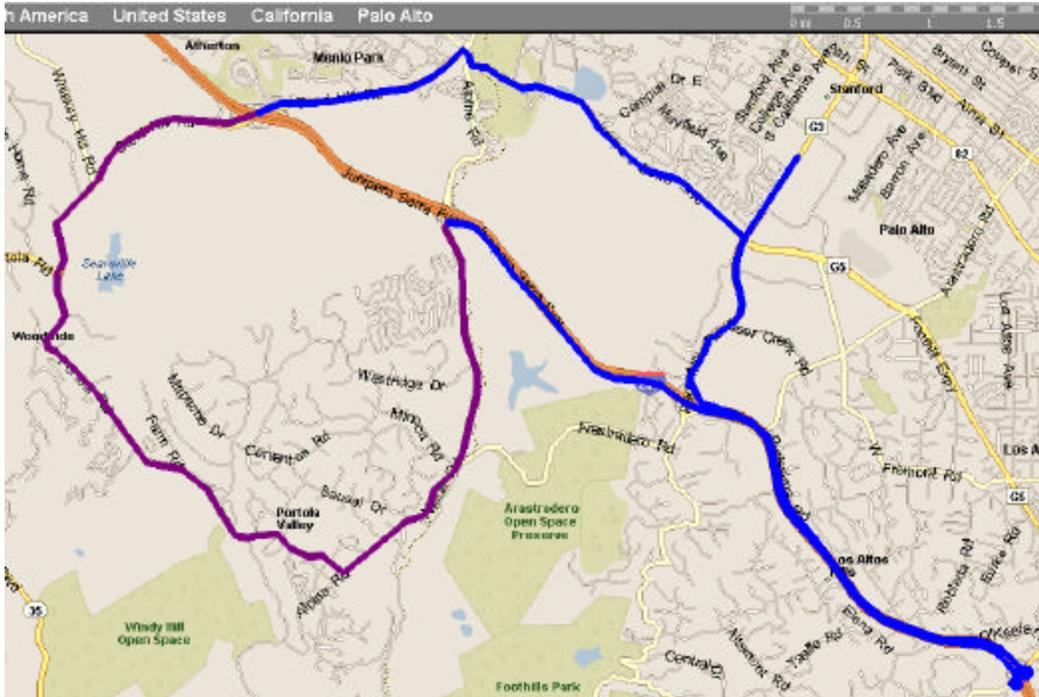


Figure 2-1: Palo Alto GM and Ford CSA demo routes

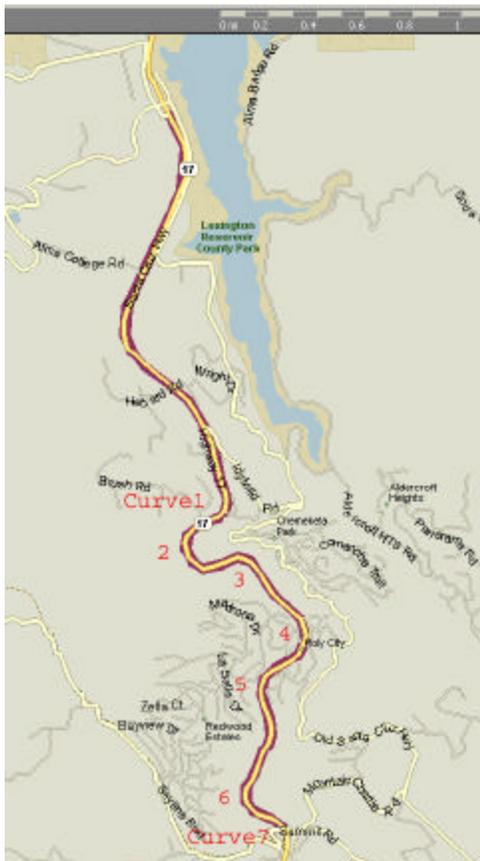


Figure 2-2: California Route 17 test area (left) and Michigan demo route (right)

2.1.3 Performance Analysis

2.1.3.1 Overall Application

The Curve Speed Assistant applications implemented as part of this project consist of three basic functions. The first function is the identification of a curve for display to the driver. The second function is providing a warning to the driver when the speed of the vehicle is determined not appropriate for the curvature of the roadway ahead. The third function is controlling the vehicle speed when adaptive cruise control (ACC) is engaged and the vehicle is approaching a curve. The following sections will focus on these three functions and generally describe how each performs with the map databases provided.

Curve Identification

Over the route chosen to evaluate the Curve Speed Warning application, approximately one hundred detectable curves were identified. Although the definition of a detectable curve from the application perspective is quite complex due to many heuristics and a large amount of filtering, a detectable curve largely consists of a roadway segment with a radius of curvature of less than 1500 m, resulting in a heading change of at least 5 degrees.

With a definition for detectable curves, six categories exist for classifying the performance of curve identification. The six categories are:

- Agreement between map- and yaw-derived road shape
- Map-based missed detection of a curve
- Yaw-rate based missed detection of a curve
- Map-matching or positioning problem causing a missed detection or false detection of a curve
- Map-based false detection of a curve
- Yaw-rate based false detection of a curve

In summary, Table 2-1 shows the performance of the curve identification function when advising the driver of the direction and presence of a curve. As shown in the figure, the map-based detection and the yaw-rate based detection agree on curve identification for 82 of the 97 samples. Although each type of input, map-based or yaw-rate based, results in a different location of the curve start, each method provided similar results for these 82 curves.

However, the function was unable to identify six of the curves when using the near-term map as the forward geometry sensor. Five of the six missed detections are curves that barely meet the definition for a detectable curve. The other missed detection is due to inaccurate curvature representation in the map database. Sections 2.1, *Road Geometry* and 2.5, *Road Curvature* (Task 7 Interim Report) discuss curvature representation in more detail.

The three missed detections using the yaw-rate based approach were also curves that barely met the definition for a detectable curve. Yaw rate bias or white noise in the sensor likely caused the missed detections in these cases. This also indicates the definition of a detectable curve should be modified.

Table 2-1: Maplet requirements

Total Curves	Agreement	Map-based missed detection	Yaw-based missed detection	Map-matching or positioning causing error	Map-based false detection	Yaw-based false detection
97	82	6	3	6	5	0
	84.5%	6.2%	3.1%	6.2%	5.2%	0.0%

The map-matching function caused another six curve samples to be missed. Most of these instances occur when the vehicle is entering or exiting limited access roadways via on/off-ramps. The map and GPS accuracy for the near-term map database does not allow the map-matching function to quickly identify when the vehicle is entering or exiting the limited access roadways. This results in a significant delay when presenting the driver with curve information.

In addition to missed detections, the map-based system also identified five curves where no curve existed. The false curves were mainly due to noise in the curvature information contained in the map. These false curves also barely meet the curve definition, which indicates an adjustment in the curve definition would likely reduce the false detections. The yaw-rate based approach yielded no false curves.

Overall, the curve identification function operates effectively. Modifying the curve identification function to only recognize longer curves that traverse a larger heading change can likely solve most of the problems outlined above. Of course, map-matching problems will still exist and continue to cause errors near expressway ramps.

The analysis above identifies the percentage of time when curve can be identified. It does not identify the accuracy of the curvature or the accuracy of the start of the curve in these instances. These topics are more appropriate for the warning and control sections to follow.

Curve Warning

This function is designed to make drivers aware when they are approaching a curve at a speed inappropriate. To effectively implement this function, the map database must contain accurate curvature of the roadway. If the map database indicates more curvature than exists in the actual roadway, the warning application is likely to provide too many warnings, which result in false indications. Likewise, if the map database indicates less curvature than exists, the warning application is likely to miss instances where warnings should be delivered to the driver.

Using the same metrics as used for curve identification in the preceding section, Table 2-2 provides an overview of the curve warnings produced when using curvature from the near-term map database and when using post-processed, yaw-derived curvature. Two of the three missed detections were on curves where the map-derived curvature differed from the yaw-derived curvature by more than 30%. The six false detections are the result of transients surrounding the curve-fitting techniques used to represent the curvature. Again, map-matching problems surrounding expressway on- or off-ramps are also a source of errors.

Table 2-2: Curve speed curve warning performance

Total Curve Warnings	Agreement	Map-based missed detection	Yaw-based missed detection	Map-matching or positioning causing error	Map-based false detection	Yaw-based false detection
23	17	3	0	3	6	0
	73.9%	13.0%	0.0%	13.0%	26.1%	0.0%

Overall, the missed detection and false detection rates for this application are likely too high for deployment. The representation of curvature in the near-term map database does not appear to meet the 10% curvature error requirements set forth in the Task 2 report. Hence, the curve warning function does not operate acceptably.

Curve Control

The CSA-C (CSA Control) implementation uses the lane-level map database to determine curve speed in a manner similar to CSA-W. When enabled, the control feature uses behavioral cues from adaptive cruise control (ACC) to follow a curve in a manner similar to the way ACC follows a vehicle. The throttle and brakes are used to decelerate the vehicle to the curve speed in an appropriate manner for curve entry. CSA-C also can enable a curve-adjusted speed resumption after the curve.

The lane-level database, as it is used for CSA-C, differs from the road-level database in two significant ways. The first is the links and lanes that are curve-fit, and the second is the type of preview that is possible. Both topics are discussed later in this section.

The performance evaluation of CSA-C with regard to the map evaluation and vehicle positioning was overshadowed by having the proper vehicle preview and also by being correctly matched to the lane of travel.

Being matched to the correct lane of travel is not required when there is only one lane of travel, such as the case in most rural non-freeway roads. But the study was limited to the lane matching of ADASRP that, when not matched to a lane (as often happens in tree-lined areas in California and the CAMP lake area), the preview ahead information is turned off instead of gracefully degrading to road-level performance. For this reason, the CSA-C evaluations and demonstrations occurred on freeways.

CSA-C operates on two primary map-derived pieces of information—the curve speed and the distance to curve. Figure 2-3 is an example of the CSA-C performance on an entrance ramp from Sandhill Road in Palo Alto to southbound I-280. The yellow line that ramps down from 150 m shows the distance to the curve, going to zero very close to the point where the vehicle yaw rate increases to negotiate the actual curve. This is the correct detection of a curve start. The other component of map-derived information is the curve speed. Starting at an arbitrary 70 m/s value, the curve speed is calculated as the vehicle approaches the curve to be approximately 14 m/s. The blue vehicle speed curve can be seen to increase (it is resuming after a prior curve) until just before the time equals 290 seconds, at which time the brakes come on (red part of the vehicle speed profile) to slow the vehicle to the curve speed. The yellow portion of the vehicle speed trace is maintaining curve speed. When the curve is over (using look-ahead), the vehicle resumes its set speed prior to the curve.

CSA-C performance was quite good in the areas in which it was demonstrated. Curvature extraction (when having the proper preview) performed well, and it was possible to deal with most of the curvature anomalies in transitions, but the numerical curve fit issues need to be resolved to relieve the burden on curve filtering.

CSA-C performance was not entirely adequate in exit ramp scenarios where factors other than the curvature have an influence on vehicle speed. Ramp status, controlled access, and high-speed connector flags of the road class mapplet were used with mediocre success in altering behavior outside the curve speed. A new mapplet – Stopping Location from the Stop Sign Assistant (SSA) and Traffic Signal Assistant (TSA) applications – was used to help in identifying exit ramps where the vehicle may need to slow down more than the curve speed.

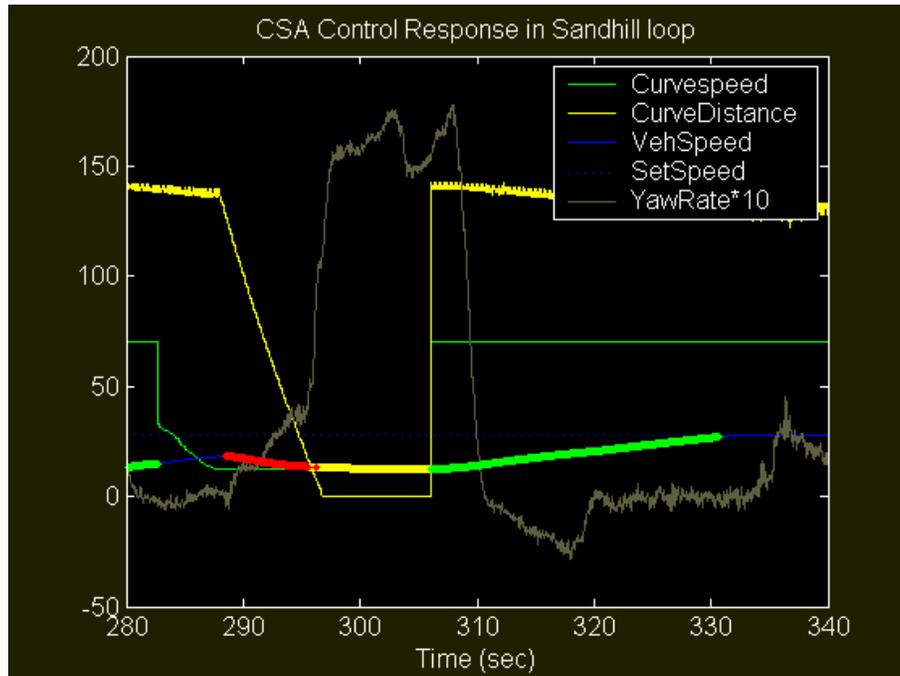


Figure 2-3: CSA-C curve following the California Sandhill Road ramp

CSA-C curve following the California Sandhill Road ramp.
Units for speed is m/s, distance is meters, and yaw rate is 10° deg/sec

2.1.3.2 Mapplet-by-Mapplet

Road/Lane Geometry and Curvature

All road and lane geometry is defined by spline representations. The spline form makes it possible to derive road position coordinates at any point along the spline. The cubic b-splines used in EDMap allow for mathematically explicit reconstruction of positions, headings, tangents, and curvature. It is from the spline representation that the curvature is derived. The curvature is not delivered explicitly as a mapplet. Likewise, road direction (heading) is also calculated from the spline form.

Task 2 Specification - Curvature

- Near-term – Within 10% of "Ground Truth" and "Fair"
- Mid-term – Within 5% of "Ground Truth" and "Fair"

where:

- Ground truth relates the accuracy of the curvature values between the definition in the map and the reality on the road. Reality is nominally defined for the road as it can be measured using the yaw rate curvature approximation.
- Fair curvature, sometimes referred to as smoothed curvature, describes the need to fairly represent the curvature in the way the road is driven at a macro level. For a straight road going into a curve and then through the curve, the curvature values should capture steady state shape, and accommodate transitions appropriately. For CSA, the curvature values are used to calculate the curve speed and to detect the extent of the curve.

Near-term

The Curve Speed Assistant's curve identification function uses road curvature to determine where curves are in relation to the vehicle. The warning function uses road curvature to estimate the lateral acceleration the host vehicle will experience as it traverses the curve. From the application perspective described in previous subsections, road curvature appears accurate for the majority of the curves encountered. However, systemic problems exist that prevent the curve warning application from directly using curvature derived from the splines.

Figure 2-4 shows two examples where curvature is not properly represented. In the figure, the images correspond to the top-down view beneath them. Inside the top-down view, arcs are drawn at 50, 100, 200, and 250 m indicating the range from the center of the host vehicle. The red line indicates the center of the map's road representation, with the green lines orthogonal to the road center being representative of the curvature derived from the spline. The first example on the left shows a typical curve represented by two low-curvature segments with a discontinuity between the segments. The discontinuity causes the curvature derived from the splines to be much less than the actual curvature. The example on the right in the figure shows how a gradual S-curve appears to be a gradual curve to the left instead of two consecutive curves with differing directions.

Based on this experience with geometry representation, more work must be done to improve the methods used for representing curvature to enable the curve warning functionality. There were also instances of curvature identification errors that were not the result of curve fitting, but rather the result of the database structure not capturing "as driven" curvatures. An example can be found in Appendix F, *CSA Evaluation*.

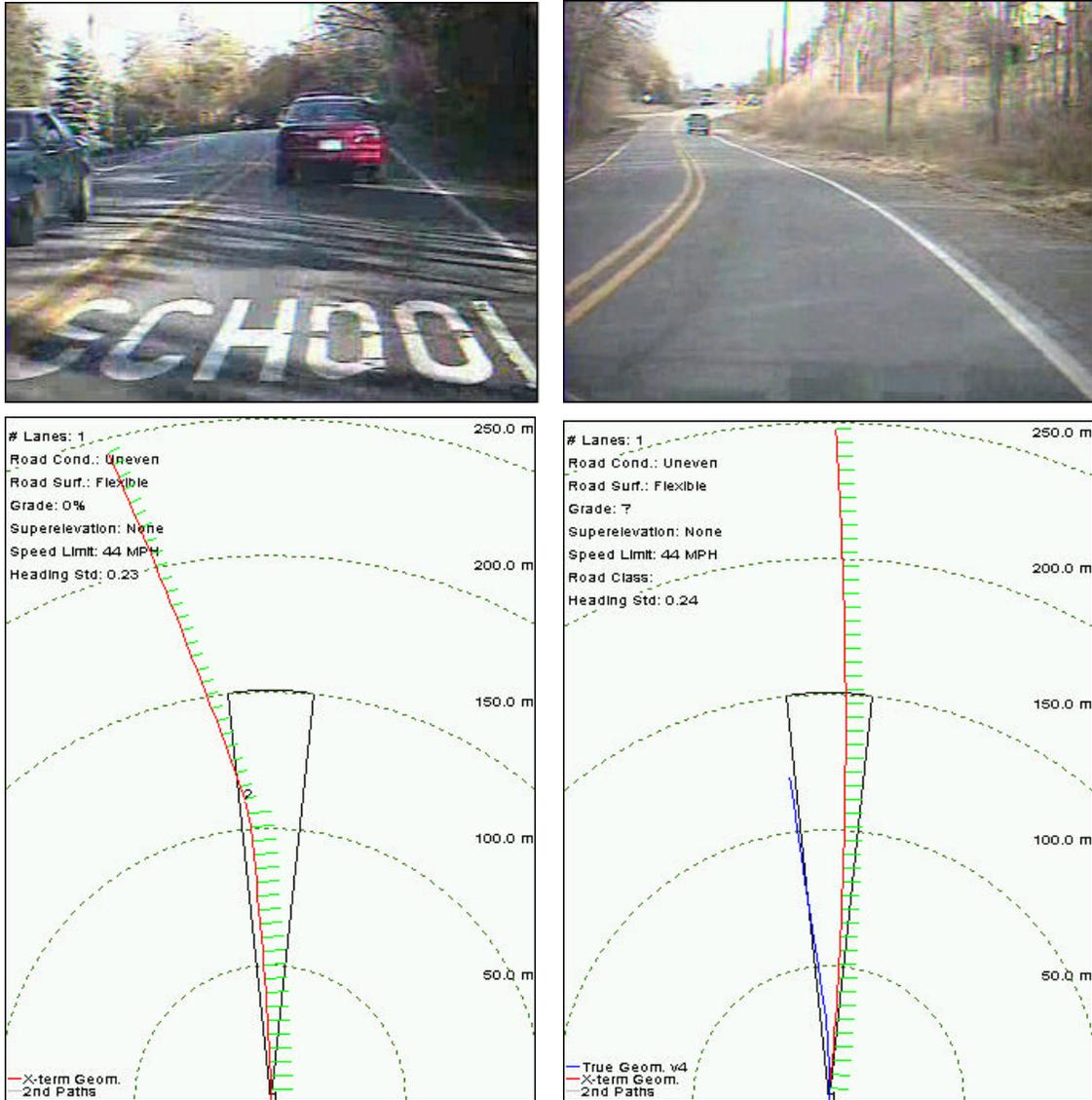


Figure 2-4: Incorrect near-term curvature representation

Mid-term

The mid-term map database was not built out to the extent of the near-term road-level database, and hence the curvature analysis is based on a set of fewer curves. The Palo Alto demo route results are shown in this subsection.

Figure 2-5 and Figure 2-6 are the respective geometry and curvature plots for the Sandhill Road ramp shown in Figure 2-3. The curvature plot shows the steady state curvature value was captured well (yaw rate confirmed at 50-meter radius of curvature), but that there was a curvature spike at the loop exit (in red) at the lane level. Curve fit spikes such as these were common in mid-term geometry transitions, and need to be minimized in future implementations. The CSA-C algorithm can filter through most of the spikes as long as the spikes are of short duration (short length along road), but curve entry and exit detection are compromised.

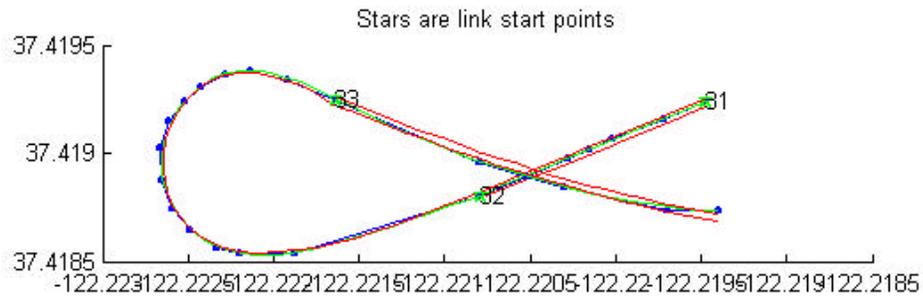


Figure 2-5: Sandhill Road ramp to southbound I-280 geometry

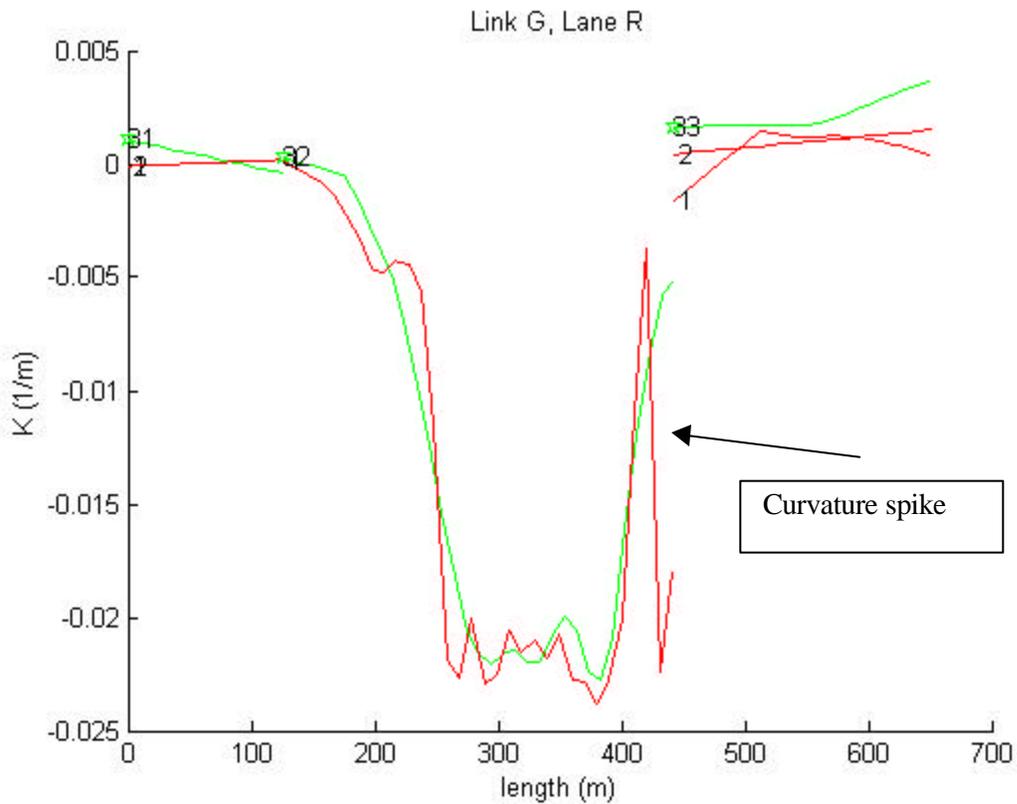


Figure 2-6: Sandhill Road ramp to southbound I-280 curvature (1/m)

The curve accuracy and fairness requirements for CSA-C can be the same as for CSA-W, however, the absolute geometric position accuracy needs to be maintained at or near the current lane level specification. The reason is that WHICHLANE positioning still needs to occur in order to properly place the vehicle in the lane. If WHICHLANE vehicle positioning error is assumed to be 1 m (or better), then map error should not exceed 0.5 m in order to maintain half lane accuracy (1.5 m = half a lane width).

Number of Lanes**Near-term**

The number of lanes mapplet is not used by the Curve Speed Assistant application. Although potential exists for improving the application by utilizing this mapplet, efforts to implement this mapplet in the applications were sacrificed in an effort to improve methods for developing and using the road geometry and road curvature information.

Mid-term

The number of lanes mapplet was not used by the CSA-C version. It is likely, however, that the number of lanes will be used in future CSA implementations to help with getting the proper curve preview.

Road Condition**Near-term**

The road condition mapplet was not used by the curve warning function. In general, the impact of road condition on braking ability is not understood in the context of curve warning. This mapplet should be removed as a requirement for curve warning.

Mid-term

CSA-C did not use road condition, and does not foresee its use in the future.

Road Surface Type**Near-term**

The road surface type mapplet was not used by the curve warning function. Future implementations will likely only need to differentiate between paved and unpaved roadways.

Mid-term

The road surface type mapplet was not used in CSA-C. It does have potential use in an estimate of lateral acceleration threshold for low μ (mu, coefficient of friction) roads such as gravel.

Road Grade**Near-term**

The curve warning function uses grade to adjust the assumed braking intensity expected by the driver when reducing the speed of the vehicle before entering the curve. If the vehicle is driving uphill, a positive grade, the curve warning will be delivered to the driver later than if the vehicle were on a flat surface, since less braking force is required to reduce the speed of the vehicle. Likewise, the curve warning will appear earlier when the vehicle is driving downhill.

Although the Michigan test area had few graded sections, grade did have a small impact on the delivery of warnings to the driver. From the set of 23 curve warnings identified in the curve warning function discussion, nine of the curve warnings were in the Michigan area. Of these nine curve warnings, four of them were affected by the grade contained in

the map database. The most affected warning changed its timing by 400 milliseconds from the baseline warning while one warning changed by 200 milliseconds, and two changed by 100 milliseconds.

Unfortunately, road grade data was not present in the California near-term database when data collection took place. As a result, no analysis could be performed in the California environment.

The changes in the timing of the warning in the Michigan environment do not warrant collection of this maplet; however, grade is an important piece of information usable by the curve warning function. Based on the minimal impact of grade, the accuracy for grade should be relaxed to 6% increments instead of the original 2%.

Mid-term

CSA-C did not use the grade maplet as the feedback control part of the algorithm adjusted for grade as a disturbance. Grade to the -5 to 5% level need not be in the database for feedback control purposes. It would be useful to have advance knowledge of large grade changes, in the 5% range, to feed forward to the controller.

Superelevation

Near-term

In the near-term map database, superelevation could have one of three values: no superelevation, positive superelevation, and negative superelevation. Positive superelevation implies the superelevation is increasing the centripetal force on the vehicle as it traverses the curve. However, the superelevation maplet did not benefit the Curve Speed Assistant application as expected. As collected, the application was unable to determine when the superelevation had an impact on the vehicle's performance. Likely, this is due to poor guidelines used for classification of the positive and negative superelevation values. Future collections of superelevation might use the same three-level classification, but should reserve the positive and negative levels for roadways where the superelevation approaches +/-10%, which is outside the normal case.

Mid-term

Superelevation in the mid-term database was specified in the 1% granularity; however, the CSA-C algorithm did not make use of the data due to its low impact on curve speed. Because curve speed is much more influenced by the gross lateral acceleration threshold for the vehicle, its conditions, and the driver, the superelevation effect was essentially below the noise threshold for the application. It is possible that extreme road bank scenarios outside normal highway guidelines need to be in the database rather than all the values.

Road Class

Near-term

The road class maplet was not directly used for curve identification or curve warning. However, map-matching does directly benefit from the road class maplet when attempting to determine the future path of the vehicle. Data quality for this maplet was appropriate for its uses.

Mid-term

Road class was of use to CSA-C for the purpose of detuning the application performance in transitions, such as exit ramps. Here are some ideas to consider—a more "appropriate" classification of ramps for different actions under ACC/CSA, for example:

Exit ramp (from continuous access to non-continuous access roads)

- o Ending in stop sign with stopping location
- o Ending in traffic light with stopping location
- o With no stopping location

On ramp (from non-continuous access to continuous access roads)

- o With stopping location (metering system)
- o With no stopping location

Speed Limits**Near-term**

Speed limit information was not used directly by the curve speed warning algorithms developed. Instead, speed limit information is used in an advisory sense to display the posted speed limit to the driver of the vehicle when the vehicle approaches a curve. For this reason, the accuracy requirements indicated in the Task 2 report are too stringent. An advisory functionality for speed limits can tolerate a location error of 50 m.

As witnessed in this application, sometimes a human is not able to immediately comprehend the applicability of an advisory speed limit. For instance, if a roadway consists of a curve left followed by a curve right, confusion may be created for the driver as to which curve the advisory pertains.

The near-term map applications using advisory speed limits also suffered from the inability to comprehend the extent of the advisory speed limit. Part of this inability stems from the poor design of the communication method for transmitting speed limit information from the near-term database to the near-term applications. The communication mechanism clearly identified when an advisory speed limit began but did not communicate when the advisory speed limit ended. As a result, the application was not able to predict when the host vehicle was leaving an advisory speed limit area.

Mid-term

The mid-term implementation of CSA-C was plagued by similar speed limit limitations, as was CSA-W. In CSA-C, the primary attempted use of speed limits was to return the vehicle to a valid speed after a curve. The map-derived curvature was sufficient for the curve speed (no check with advisories). Coming out of the curve, however, consistent and continuous knowledge of the current speed limit would have been useful.

Since most ramps do not have posted speed limits, EDMap defined ramps to have zero, or unknown, speed limit. Advisory speed signs were found to not be very helpful as the curve speed calculation performed this function, and advisory speeds are not uniformly posted. The ramp speed limit problem is exacerbated by the high-speed connector road class that often has zero speed even though it's an at-speed road section. If the speed limit maplet is to provide a continuous speed limit profile, modification to the ramp road class will be required.

Stopping Location

CSA-C added the stopping location maplet as it was useful in altering speed behavior on exit ramps where traffic is approaching an intersection with a stopping location. The accuracy specification is not as stringent as for SSA or TSA, and can be relaxed to 10 m.

2.1.3.3 Vehicle Positioning

This section describes aspects of road and lane level matching that influenced CSA performance. A treatment of vehicle positioning as it affected all applications is presented in Chapter 4.

Near-term

The performance of the NTBox combined with the ADASRP to perform near-term WHATROAD positioning was a star performer in the evaluations. Much of that credit goes to map-matching that contained errors on curving roads.

In simple scenarios, the map-based system is able to map-match the vehicle to the correct road segment and provides the applications with information in the forward direction. However, as outlined in previous subsections, the map-based system is limited near ramps and bifurcations. Figure 2-7 shows examples where the system is unable to map-match itself to the correct roadway near ramps.

The scenario on the left shows the vehicle exiting a ramp to the right of the main roadway. The map-matching system assumes the vehicle has stayed on the main roadway and delivers a preview that indicates the roadway is straight and heading to the left. However, the actual ramp heads to the right and contains a sharp curve. In this situation, the curve identification and curve warning functions have no information about the curve.

The scenario on the right in Figure 2-7 shows the vehicle maintaining its position on a major expressway. However, the map-matching system has incorrectly map-matched the vehicle to the ramp veering right that the vehicle has already passed. In this circumstance, both roadways are straight. If the ramp contained a curve, the application would likely provide a false curve identification or curve warning to the driver.

Both of these scenarios contributed to the missed detections and false identifications described in the previous subsection. It is likely this problem will continue to exist in any implementation of these functions. To reduce the number of mistakes, the map-matching system may add functionality to learn the driver's daily driving pattern or use routing information entered into a navigation system. However, each of these improvements is limited in capability and is not likely to solve this problem.

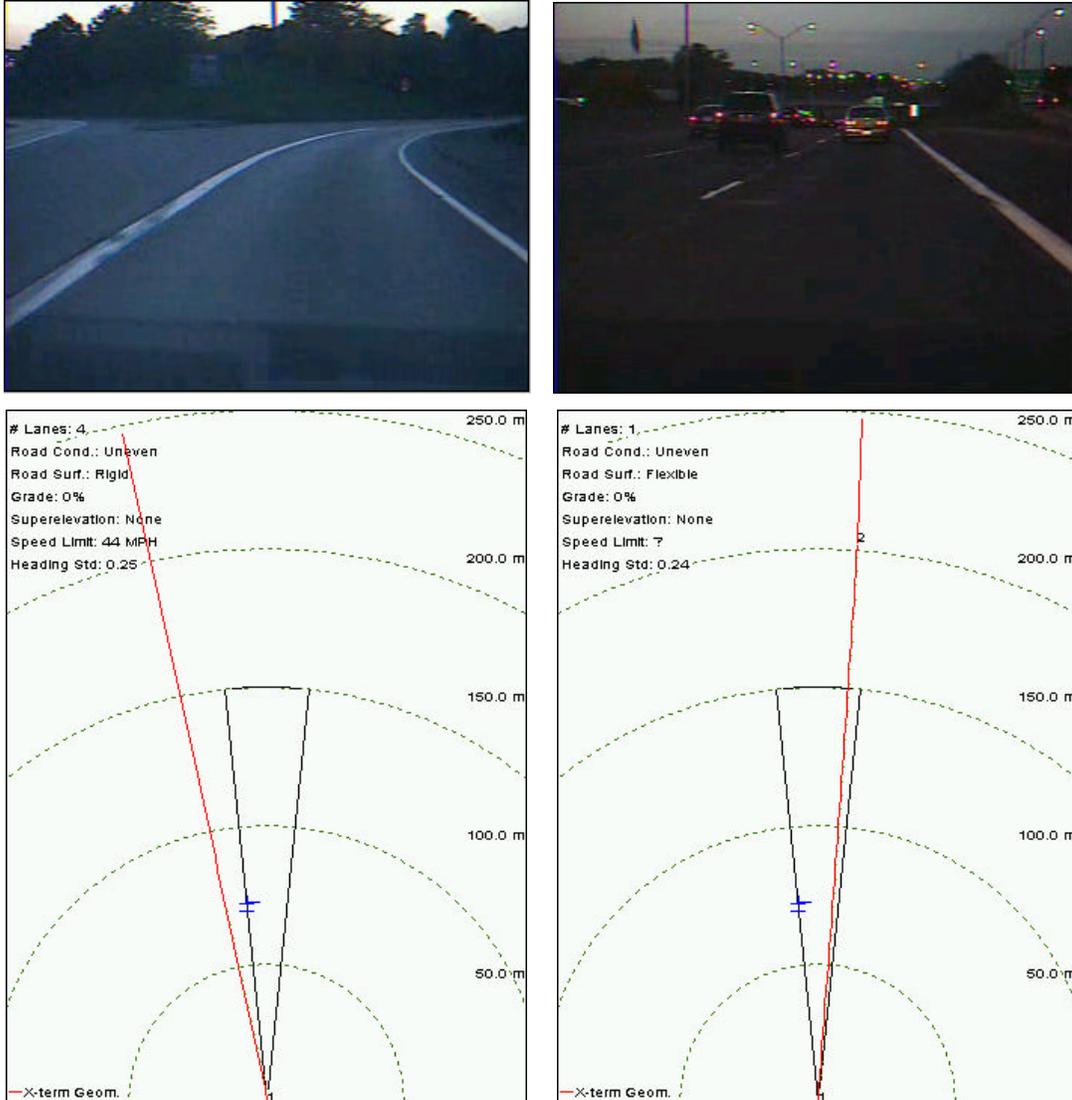


Figure 2-7: Map-matching incorrect near ramps

Mid-term

CSA-C was successfully demonstrated on road-level maps where the curvature mapplet met the CSA-W requirements. As was stated earlier, however, CSA-C remained a WHICHLANE application due to the increased need for proper preview in the control mode. In the CSA-C application, lane-level information provided a significant improvement to the proper preview problem. The effect of improper preview is potential annoyance in CSA-W; however, the effect in CSA-C is a potential application of the brakes when the curved path predicted is not the actual vehicle path. This is a significant limitation for CSA-C.

Using lane-level maps and vehicle positioning matching the vehicle in a certain lane, the electronic preview horizon can be focused to the lanes ahead as opposed to just the road segments ahead. Figure 2-8 shows the impact of using lane information to predict the preview.

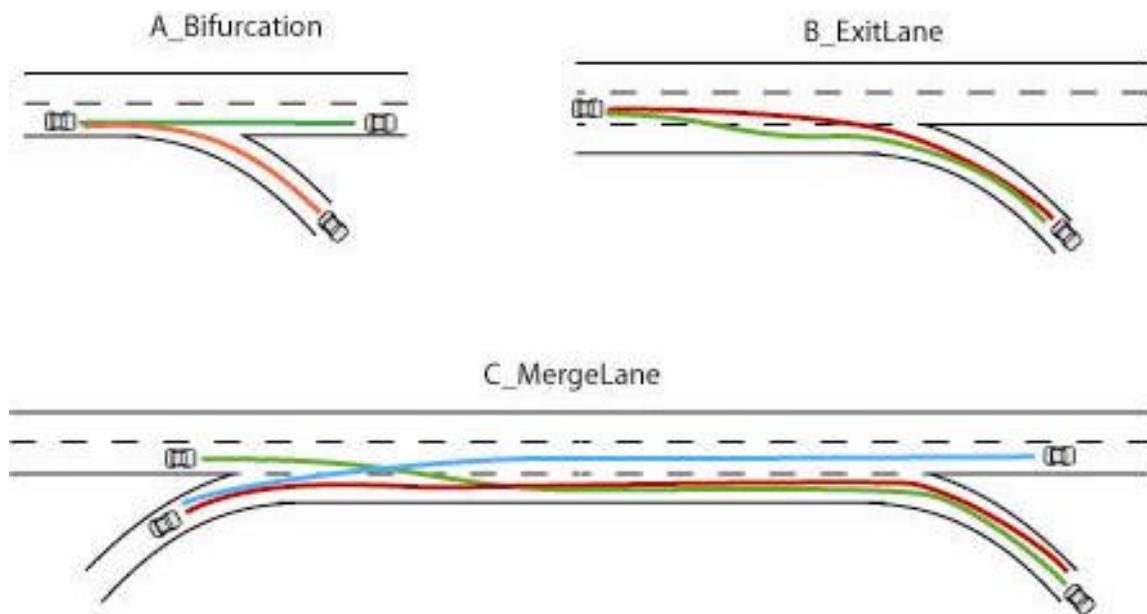


Figure 2-8: Lane-level preview aiding

Scenarios B_ExitLane and C_MergeLane both provide the appropriate preview as soon as the vehicle gets into the “ramp only” lane. Timing of the preview can be affected by how soon or late the vehicle enters the lane, as evidenced by the respective green and red paths. In C_MergeLane, the exit ramp is not detected as the vehicle enters the road and moves to the center lane, as shown in the blue path—no false curve—and hence no incorrect deceleration in the middle of the freeway.

2.1.4 Possible Deployment Options and Potential Safety Benefits

The previous CSA discussions focused on performance given the maplet and vehicle positioning capability achieved in the EDMap implementation. The analysis assumed that the capability needed to exist as specified for all roads for the respective CSA-W and CSA-C modes. This section of the CSA evaluation explores potential deployment scenarios from the perspective of how a CSA application could migrate to a product from today’s navigation based map. The migration path could be viewed also as an effort to minimize the additional effort to build a CSA capable map without adversely affecting potential safety benefits.

2.1.4.1 Selective Road Coverage

A fundamental EDMap assumption had been that all roads would need to be mapped at the required level for a given application. Moreover, maplets for all applications were assumed to be delivered for all roads. For CSA in particular, it is possible to relax the “all road” assumption. Relaxation of the all road assumption is motivated for two reasons. The first reason is for map database rollout logistics. The more roads that have to be digitized, the longer it will take to cover the United States with an effective CSA system. The second motivating reason is the additional burden CSA-C places with the lane level requirements. Lane level has higher effort to create on a per driven mile basis than road level databases.

One commonly mentioned road coverage relaxation is freeway only coverage. Freeways comprise approximately 3% of the United States road network (see Section 3.4, *Database Creation Effort*) and could be mapped relatively quickly. Yet from a safety benefit point of view, only approximately 7% of CSA coverable crashes are on freeways.

A more favorable approach comes from examining the speed limits where road departure accidents occur in curves or, in an opposite sense, where accidents in curves happen less frequently. According to Najm and Schimek (2001), approximately 14% of the accidents involve losing control on roads where the posted speed limit is 25 mph or less. The significance of this statistic emerges when one considers that approximately 75% of roads in the United States fall within the 25 mph or less, essentially residential street, category. Therefore, it is estimated that 86% of CSA addressable crashes could potentially be covered by mapping 25% of the network. See the Appendix F, *CSA Evaluation*, for calculations. The impact on a potential CSA deployment timeline would be beneficial for both CSA-W and CSA-C. The reduction of potential safety benefit is tempered by the low speed crash type and the potentially accelerated rollout of CSA. The potential advantage with regard to the map effort is described in Section 3.4, *Database Creation Effort*.

2.1.4.2 Hybrid Road-level / Lane-level Map

Selective road coverage might aid deployment timelines and/or effort for both CSA-W and CSA-C, but the lane-level requirement for CSA-C remains in effect. One possible mitigation for the lane-level premium is to consider that lane-level map capability is really only needed in road sections where the lane information can help provide the proper preview as was shown in Section 2.1.3.3. When there is only one lane of travel ahead, then the road-level derived preview is adequate for CSA-C.

This observation leads to consideration of a hybrid map that contains both road level segments and lane-level segments. The lane-level segments would exist only where multilane preview information could resolve bifurcation issues. Where lane bifurcations do not happen, then standard road-level maps could suffice.

This hybrid form of road-level / lane-level map was not implemented as part of the EDMap project, but it is deemed to be a feasible solution to further reduce CSA dependency on lane level maps. A caveat must be imposed on vehicle positioning. CSA-C retains its WHICHLANE requirements on vehicle positioning (<1.0 m) in order to correctly lane match.

2.1.5 References

Najm, W., Schimek, and Smith, D.L.; "Definition of the Light Vehicle Off-Roadway Crash Problem for the Intelligent Vehicle Initiative", Transportation Research Board, Paper No. 01-3194, U.S. Department of Transportation, 2001.

2.2 Stop Sign Assistant

2.2.1 Application Description

This Stop Sign Assistant (SSA) was designed to evaluate the system as a map-enabling application. The location of relevant mapplet information is only provided by the map database. A vision system used in combination with map information has the potential for realizing a more reliable system. This sensor fusion would not only be beneficial, but prudent in designing a safety enhancing system.

It is obvious that the SSA needs to have some kind of countermeasure for mitigating conceivable negative impacts due to using map data that may not be completely correct in representing real time situations around the vehicle while the vehicle is in motion.

Some basic assumptions made when designing the SSA were that position ambiguity would be present in both the map data and vehicle positioning. An additional assumption was that there might be situations in which a preceding or stopped vehicle is present when the SSA approaches a stop sign.

2.2.1.1 Near-term Functionality

The SSA application employs a road-level map database and positioning sensors that could be available in the near-term timeframe to warn and notify drivers of the presence of stop signs and stopping locations when it appears that they may drive through such posted locations without stopping.

The SSA also warns drivers of the presence of yield signs when it appears that they may drive through a posted location without first slowing down and checking traffic conditions. The application also issues an advisory when the driver passes a stop ahead sign.

In the event of the presence of a preceding vehicle at a posted location, an on-board forward object sensor provides distance information that the application employs to determine if a warning should be issued for the approaching mapplet or for the preceding vehicle. Because this feature does not become active unless the preceding vehicle is within proximity of the approaching mapplet, this forward object-warning feature is directly tied to the map database.

2.2.1.2 Mid-term Functionality

The SSA application employs a lane-level map database considered to have more accurate and reliable content, and positioning sensors considered to be more accurate in position, which would be available in the market within the next five years at the earliest to not only warn drivers of the presence of stop signs and stopping locations, but to bring the vehicle to a stop or at least reduce vehicle speed before entering the intersection when it appears that the driver may drive through the posted locations without stopping.

The brake control feature serves as a backup to the warning function and is designed to bring the vehicle to a complete stop or reduce speed to mitigate crash impact once the deceleration threshold for the control function has been reached. In this regard, the application functions in a significantly different manner than automatic braking systems. It is conceivable that some drivers will become complacent and become dependent on the vehicle to stop automatically when approaching stop signs therefore the application of the brake was made intentionally rough to avoid such inappropriate use.

The mid-term application provides the same functionality as the near-term application in regard to yield and stop ahead signs.

The forward object sensor is a single camera vision system that measures distance to objects by performing a frame-by-frame comparison of the relative motion in the scene to determine the motion of the vehicle. This is done to estimate the trajectory of the vehicle in order to eliminate objects in the adjacent lanes.

In the event of the presence of a preceding vehicle at a posted location, the application employs a forward object sensor to first warn the driver, and then bring the vehicle to a stop or reduce vehicle speed if it appears that the driver is in danger of crashing into the preceding vehicle.

2.2.2 Application Results

The Toyota EDMap team tested the SSA over a one-year period in two different locations that exhibited significant differences in topography. The first location was the Ann Arbor/Farmington Hills vicinity in southeastern Michigan. Open sky and flat terrain characterize this area. The second location was the Palo Alto, California area. Significant tree coverage and hilly terrain characterize this area. The two areas represented two vastly different results in terms of performance of the application.

2.2.2.1 EDMap Areas

After a number of adjustments, the performance of the warning feature in both locations met expectations as long as the EDMap databases were accurate and the position sensors performed within their specifications. Regarding the map data, only the demo routes were given special consideration by NAVTEQ to eliminate as many errors as possible.

2.2.2.2 Position Errors

Excluding unusual lane dependent situations such as an intersection with a stop sign for the through lanes but a yield sign for a right turn lane, point attributes such as stop and yield signs are more likely road-level rather than lane-level attributes. Because the map-matching function could mitigate lateral positioning errors along the road, most positioning errors were longitudinal errors. But for the mid-term lane-level application, lateral position errors also played a critical role in the ability of the SSA application to function. If lateral position of the lane geometry were off by a significant amount, (i.e. greater than 4 m difference between lane center and position reported by the Mid-term Honeywell PAPS positioning sensor) maplet information would no longer be available to the SSA application.

2.2.2.3 Vehicle position errors caused by the Mid-term Positioning Sensor (Prototype MEMS IMU INS by Honeywell)

Honeywell developed the prototype positioning sensor for the mid-term application. This prototype sensor was originally designed as an embedded sensor/system for such applications as navigation systems. Therefore, there is an assumption that the vehicle will be started up at the same place as where it last shut down. According to Honeywell, the sensor might encounter resets if the startup position is different from the last shutdown position.

Position accuracy of this prototype sensor was good as long as it worked with Real Time Kinematics DGPS. However environments such as heavy tree cover or unavailability of DGPS corrections obtained from the cellular network resulted in differences between the IMU solution and the GPS position. When the difference became significant, IMU resets would occur. Under these circumstances the SSA couldn't operate properly.

2.2.2.4 HMI Functions

The Human Machine Interface (HMI) is adequate for the intended purpose of demonstrating the functionality of the application; however, much work in this area is required before a system can be deployed.

2.2.2.5 Warning Capability and Position Accuracy Criteria

Regarding SSA safety benefits, warnings need to be issued before the subject vehicle enters the intersection. In order to issue a warning at the appropriate time, the position at which the warning is issued must be somewhere between the position of the vehicle and the stopping location, taking into account considerable positioning ambiguity.

Assume that a warning is issued when the amount of deceleration required to bring the vehicle to a stop as it reaches the stopping location is 0.2G (1.96m/s/s) and that the SSA's minimum warning enabling speed is 20 km/h (12.5 mph). The acceptable position error would be 7.8 m.

Under the same assumptions, if the position error were 15 m, the minimum warning enabling speed would need to be at least 27.6 km/h (17.3 mph).

In terms of the brake control feature, assuming that the brakes are applied when the amount of deceleration required to bring the vehicle to a stop as it reaches the stopping location is 0.3G (2.94 m/s²) and that the SSA's minimum warning enabling speed is 20 km/h, the acceptable position error would become 5.25 m.

2.2.3 Possible Deployment Options and Potential Benefits

The original intent was to demonstrate the application in both California and Michigan as a warning system only using the road-level map data and currently available positioning sensors and as a control system using the more accurate lane-level map data and the more accurate mid-term positioning sensor.

It was felt that the near-term map database and positioning sensor could not provide the accuracy needed to properly control the vehicle to a stop before entering the intersection or preventing a rear-end crash due to stopping too early for the stopping location.

However, it was discovered during the evaluation of the application in California that after performing the map matching function (using the near-term map database and the physical positioning of the vehicle on the route), the system could adequately reduce the lateral position error to perform both the warning and control functions in the demo area.

The longitudinal position errors did not affect the warning function as much it did the control function. In order to provide effective control, a more accurate and robust position sensor is definitely needed as well as accurate map data in terms of position and content.

2.2.3.1 Warning Strategy and Safety Benefit

A warning should be issued only when the system determines that certain conditions that would warrant a warning have been met. False alarms will simply annoy and create an environment in which legitimate warnings might go disregarded. It is conceivable that warning for individual drivers might be different. The warning conditions/timing could be adjustable but this could create a trade-off with the original safety benefit.

System operability is the paramount factor regarding safety benefit. There is no safety benefit if the system doesn't work due to poor positioning or inaccurate map data. Conversely, there is no safety benefit if excessive false alarms render the system unreliable in the eyes of the driver who

then disregards all warnings. Once a system of acceptable functionality becomes available, mitigation level becomes the primary consideration.

2.2.3.2 Brake Control Function (as part of the warning system)

Even though the brake control feature was initially intended for use only with the lane-level map database and mid-term position sensor, results indicate that in a crash mitigation capacity the brake control feature can be incorporated into the SSA warning application with road-level maps (10 m accuracy) if more accurate map data (5 m accuracy) and a more accurate and robust position sensor (1 - 3 m) is used. The overall position ambiguity (15 m) associated with the near-term position sensor and the near-term map database employed in this project is too great to be effective in a control application. With this level of uncertainty, the danger of overshooting a stop sign or the annoyance of stopping too early is too great to be effective as a crash avoidance feature.

In this regard, the control brake feature needs to be considered as a part of the warning and an additional potential benefit for the system because of potential limitations caused by data errors and position ambiguity.

2.2.3.3 Data Errors

Numerous errors related to the placing of maplets in the map databases were encountered throughout the EDMap project. There were a significant number of errors of omission where maplets that should have been on the map were missing. There were also a significant number of errors of commission where maplets were placed in the database where they should not have been.

To counter such problems, map applications may need to be designed to handle such potential issues. In order to avoid critical impacts on the safety benefits of the SSA due to embedded data errors, other reference inputs such as vision/radar could be used to confirm the prevailing conditions (e.g., presence or absence of a stop sign) in real time.

2.2.3.4 Map Matching

The map matching function for the WhatRoad mode of operation was a critical factor in the relative success of the SSA during the California demonstration. This function essentially reduced lateral vehicle position error to maintain the vehicle on the road. As long as the vehicle remained on the road, the Advanced Driver Assistance System Research Platform (ADASRP) could provide the maplet information needed for the application to determine the proper course of action based on vehicle speed and distance between the vehicle and the approaching maplet.

For lane-level applications, lane-level map matching also helped to maintain the vehicle on the route as long as the vehicle stayed in the lane.

2.2.3.5 Integrated Position Error by Vehicle Positioning and Map Data

Stop Sign Map Data Position Error (Near-term)

A factor in the relative success of the SSA demonstration was the physical positioning of the stop signs along the route. They were generally posted approximately 3 m (10 ft) prior to the intersection, especially in Palo Alto. This provided some additional latitude when the ambiguity of the positioning sensor increased, causing the timing of the warnings to fluctuate from somewhere before or much worse, after the stop sign. Figure 2-9 below shows the total position ambiguity, which includes vehicle positioning ambiguity and map data position errors. The values shown in the figure represent the

distance to the maplet as reported by the system while the vehicle was stopped at the physical location of the maplet. Positive values indicate the reported vehicle position as being before the maplet and negative values indicate the reported vehicle position as being past the maplet. Using stop sign #11 as an example, on the first measurement, the system reported the vehicle position as being 4 meters before the maplet and 8 meters past the maplet on the third measurement even though the vehicle was stopped at the physical location of the sign on both occasions.

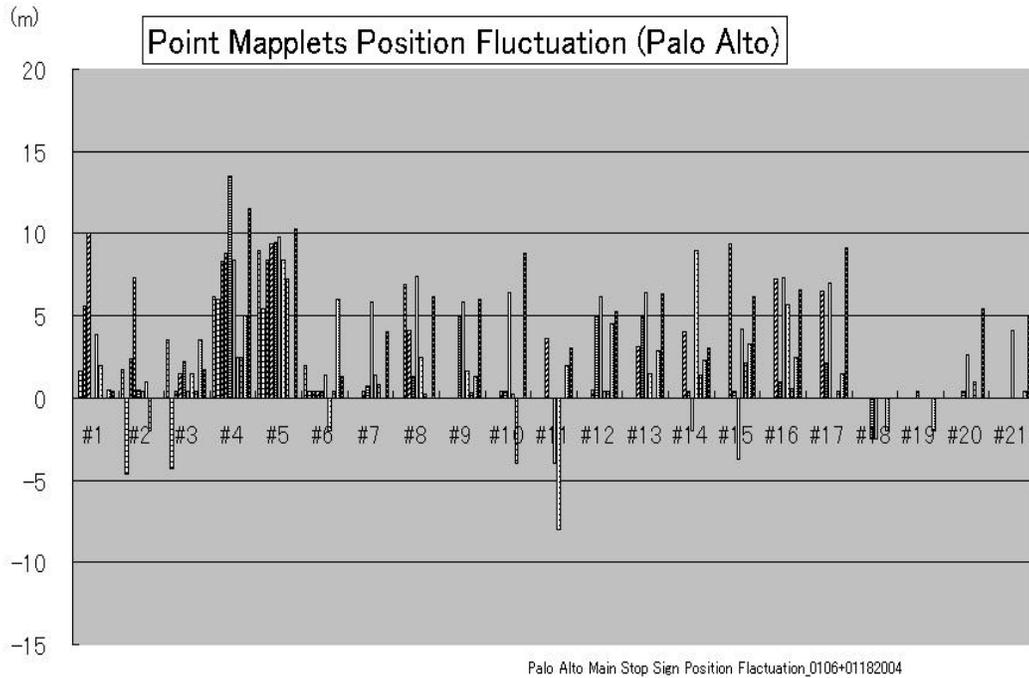


Figure 2-9: Near-term distance to the stop sign at 21 locations in Palo Alto

Due to safety concerns, the SSA team chose four-way stops in Palo Alto to conduct the control portion of the demonstration. If the vehicle overshot the stopping location, there would be much less chance of hitting another vehicle in the cross street than at two-way stops. However, at the test driver's discretion, the team also demonstrated the brake control function at two-way stops that afforded a clear view of traffic on the cross street.

In the Palo Alto demo, there were 21 stopping locations but no stop ahead and yield signs. The SSA could demonstrate the Stop Sign Assistant as a warning system with brake control better with the near-term positioning system and map data than with the mid-term positioning system and mid-term map data.

In fact, the Stop Sign Assistant with brake control worked so well that on one occasion a DOT representative was invited to choose any route within the demonstration area. On this occasion, the application worked as expected on roads that were never before attempted. However, due to the overall position ambiguity, the system could not be expected to control the brakes consistently at all locations all the time.

The operation of the system was characterized by flawless performance at a particular location on one occasion only to stop well short of the same stopping location a few hours later and then overshoot the location on the next pass.

Based on this observation operating the brake control system with the near-term position system and road-level maps would not be feasible. In a warning-only capacity, the timing of the warnings gave the driver enough time to react in time to bring the vehicle to a stop before entering the intersection. However, for drivers who prefer to aggressively approach posted stops, the timing may be such that the warning would be considered annoying.

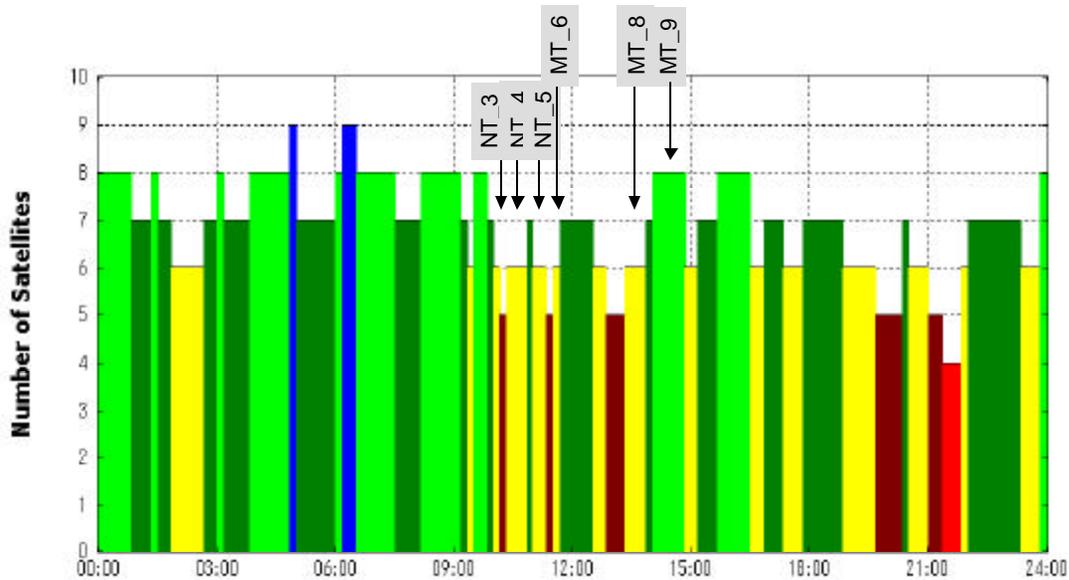
Mid-term issues in Palo Alto, California

Positioning ambiguity was an issue with the near-term position sensor in both the California and Michigan demonstration areas.

This problem could be solved with the more accurate mid-term position sensor, but while the mid-term positioning sensor was more accurate than its near-term counterpart, the mid-term sensor and map database had its own unique set of issues during the California demonstration that together resulted in a far less capable application.

The California demonstration environment was completely different from the demonstration environment in Michigan. The demonstration route was lined most of the way with trees that exceeded 6 m (20 ft) in height.

This was thought to be the cause of considerable outages of the GPS signal; however, analysis indicates that a combination of poor visibility of the sky and poor GPS satellite constellation caused the majority of outages. The sensor could not acquire a sufficient number of satellites to provide an accurate vehicle position. Figure 2-10 shows the number of GPS satellites available at a given time on January 6, 2004.



Palo Alto SSA Main Demo Area 1/6/2004

Figure 2-10: GPS satellite visibility

Figure 2-11 traces MT_6 and MT_8 show that when the number of satellites available was low, the Honeywell Prototype Automobile Positioning Sensor (PAPS) departed from the route (MT_6) or resettled when it reacquired enough satellites (MT_8). Figure 2-11 also shows that after acquiring more GPS satellites, the PAPS could trace the entire route along the same set of tree-covered roads (trace MT_9).

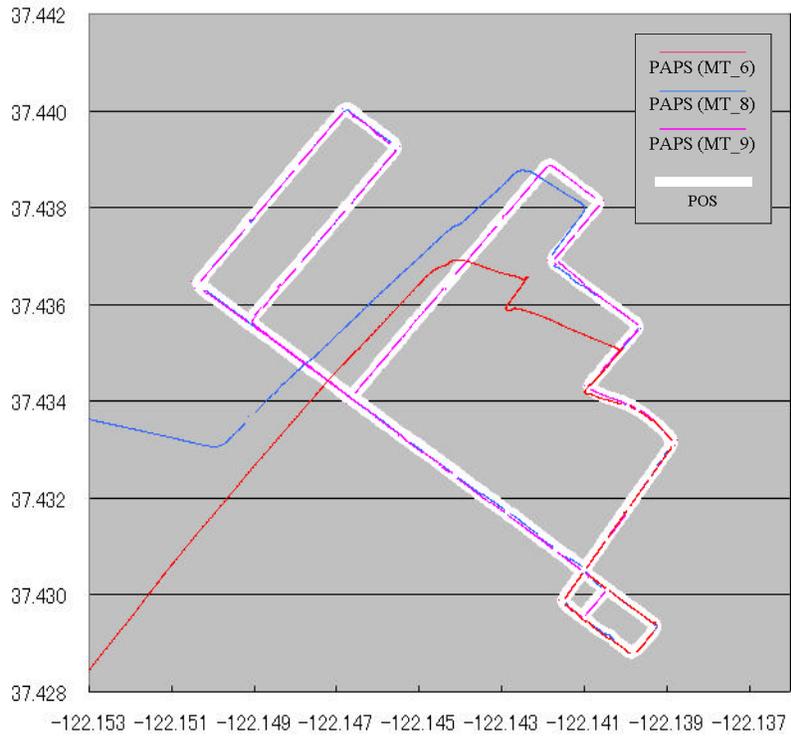


Figure 2-11: Mid-term positioning sensor route traceability along the Palo Alto demonstration route

Mid-term positioning (latitude longitude degrees) sensor route traceability along the Palo Alto demonstration route

Mid-term Geometry Issues Along the Palo Alto Demo Route

According to the MT_9 data, the PAPS reported the vehicle as being on the road 63% of the time, excluding 13% of the time when the vehicle was in intersections (see Figure 2-12).

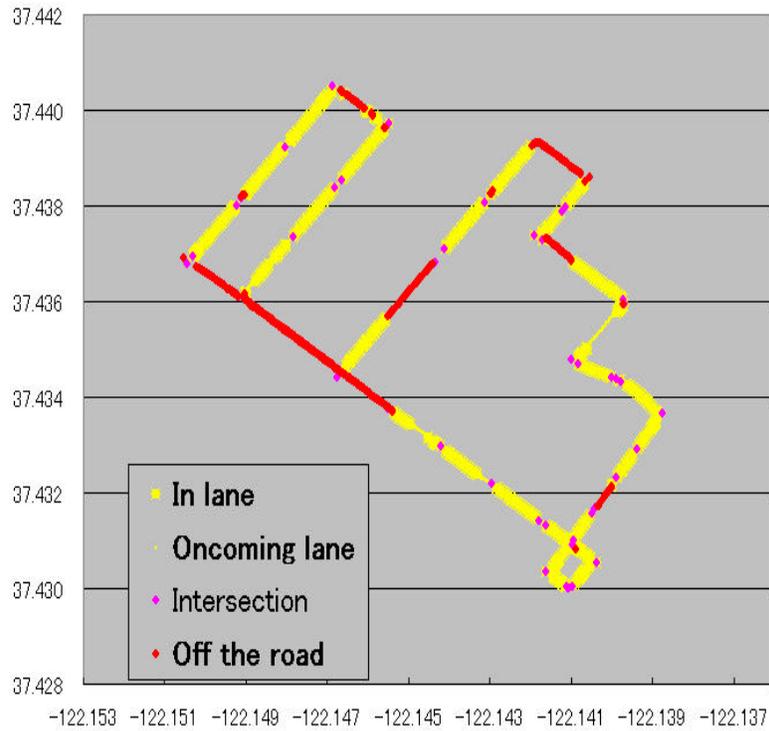


Figure 2-12: Locations of the ADASRP reported vehicle position status

Locations (latitude longitude degrees) of the ADASRP reported vehicle position status

Figure 2-13 shows the remaining 24% of the time when the vehicle was reported off the road. A comparison of the PAPS unit with TTC’s reference Position and Orientation System (Applanix POS/LV420) for these segments indicates, surprisingly, that lane geometry/lane position errors accounted for 88% (21% of the total time on route) of the time the vehicle was reported off the road. Actual drift of the PAPS unit accounted for only 9% (2% of the total time on route) of the time the vehicle was reported off the road.

Since road-level map-matching demonstrated good performance under degraded GPS signal conditions along the same demo route, the “off the road” condition could be mitigated by applying lane-level map-matching that gracefully degrades to road level map-matching, especially when there is only one lane in each direction.

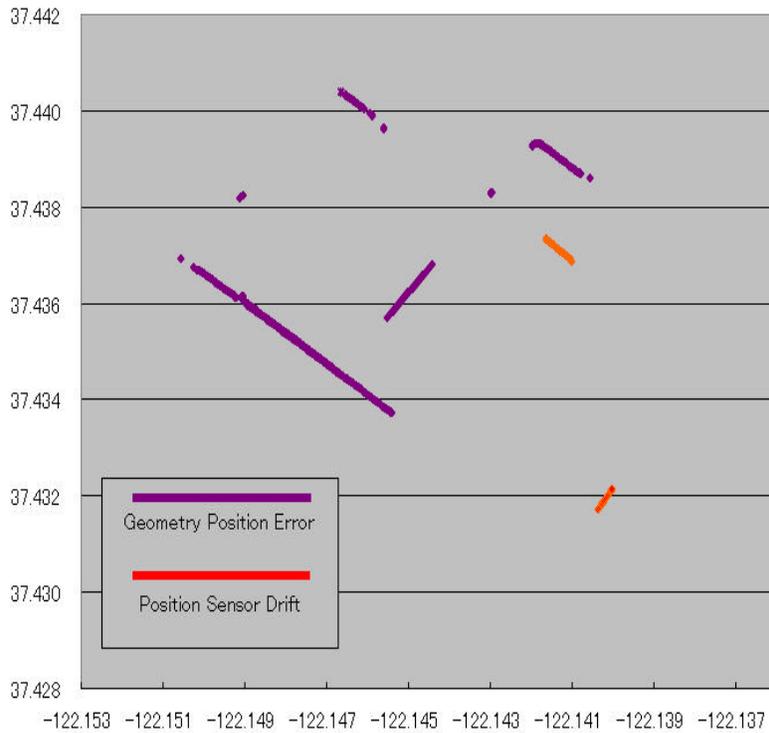


Figure 2-13: Poor geometry and PAPS deviated locations

Poor geometry and PAPS deviated locations (latitude longitude degrees)

Mid-term Position Accuracy Improvement on the Michigan Demonstration Route

Generating more accurate data would be one method of increasing the operability and the safety benefit of the SSA. But this may prove costly in terms of database maintenance.

As seen in Figure 2-14, NAVTEQ gave much more consideration to maintaining the SSA demo route in Michigan than the demonstration route in California. Positioning errors were reduced to less than one fourth that of the initial maps (from 40 m to 10 m). But the errors are still larger than the expectation of the OEM (less than 1m was the first expectation for the mid-term data position accuracy).

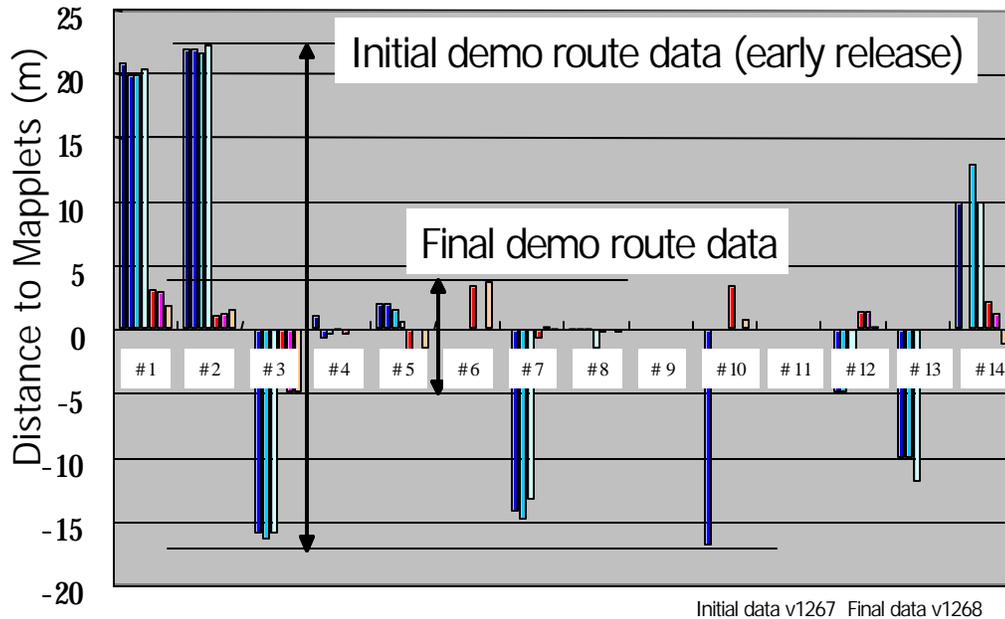


Figure 2-14: Mid-term data position accuracy improvement

Map Matching as a Counter Measures for Poor Geometry/Lane Position Errors

Poor geometry/lane positioning errors were experienced throughout the Palo Alto demonstration route. A lateral geometry error was also experienced at one yield sign along the Michigan demo route. For this particular case of poor mapplet positioning in the map database, a more accurate positioning sensor would be of no help because the position of the data itself is incorrect.

A key issue with mid-term positioning was also map matching. While some map matching was done, the system would defer to the position sensor for vehicle position when the difference between the position sensor output and map became too great (greater than 4 m). Under these circumstances, a sophisticated observer would be required to determine the current lane/location.

2.2.3.6 SSA with Forward Object Sensor

Under normal driving conditions, it is quite possible that there will be a preceding vehicle present when approaching a stop sign. Without a forward object sensor it is conceivable that drivers, who have become complacent, will expect the vehicle to stop automatically and as a result, end up rear-ending a stopped preceding vehicle because the vehicle has not yet reached a point where the control system applies the brakes.

To prevent this from occurring, the forward object sensor detects the distance/location and speed of the preceding vehicle in order for the SSA to avoid rear-end collisions by warning and/or applying the brake. Because there is no brake control in the warning application, the forward object sensor, while perhaps desirable, is not needed.

One additional factor that is seen as a requirement for both the warning and control applications is the ability to sense the condition of the road. The condition of the road surface (e.g., dry, wet, snowy or icy) is a critical factor in determining when warnings must be issued or control must be activated. The driver cannot be expected to manually input road condition. While such a sensor is needed, none are currently available.

2.2.4 Safety Benefit

At this point in time, the capability to bring the vehicle to a stop or mitigate crash impact in the event the driver does not respond in time to a warning represents a significant increase in cost for a fractional improvement in capability. While the added benefit of bringing the vehicle to a stop or mitigating crash impact under extraordinary circumstances is desirable, the cost would be prohibitive at today’s level of technology.

Evaluation of the Stop Sign Assistant application resulted in identification of the three prominent constraints in Table 2-3 that affect the application’s deployment.

Table 2-3: Deployment constraints

	Stop Sign Assistant – Warning	Stop Sign Assistant – Control
1	Inconsistent or poor map quality Longitudinal position ambiguity Errors of omission Errors of facing wrong directions Errors of commission	Critical. Could be a cause of negative impacts .
2	Positioning uncertainty. Road level accuracy needs to be within 5 m rather than the current 10 to 15 m accuracy.	The same but it becomes even more critical. Lane level accuracy needs to be within half the width of a lane (1.8 m) as a WhichLane application
3	Database development cost/level of effort	Same

Table 2-4 identifies potential mitigations to the deployment constraints identified in Table 2-1.

Table 2-4: Potential mitigations to deployment constraints

	Stop Sign Assistant – Warning	Stop Sign Assistant – Control
1	Institute a rigorous database validation process Employ a positioning metric for application use	Same
2	Disable warning during positioning ambiguity	Disable warning & control during positioning ambiguity
3	Apply the application to only specific roads Use probe data in developing databases Apply offset to mitigate an overshoot	Same
		Employ high accuracy positioning with a road-level map. However current road-level accuracy is insufficient (see above).

Table 2-5 identifies possible disadvantages to the potential mitigations.

Table 2-5: Possible disadvantages to potential mitigations

	Stop Sign Assistant – Warning	Stop Sign Assistant – Control
1	Increases effort to build to maintain database	Same
2	Disabling the system reduces safety benefit	Same
3		Increases cost for positioning system

2.2.5 Mapplets for the SSA

2.2.5.1 Relevant Mapplets

The Stop Sign Assistant (SSA) originally considered seven different mapplets as relevant to the application. Those mapplets were:

- Stop Signs
- Stopping Locations
- Yield Signs
- Stop Ahead Signs
- Grade
- Road Condition
- Road Surface Type

Through the evaluation, the SSA found that grade, road condition, and road surface type data in the map data were not so critical for the SSA functions and also the data were not accurate enough for the evaluation.

After the evaluation, the SSA only dealt with:

- Stop Signs
- Stopping Locations
- Yield Signs
- Stop Ahead Signs

2.2.5.2 Single Stop Sign Mapplet

To facilitate stopping at a posted stop sign location, it would be better to have a single most likely Stopping Location assigned. In many cases, separate stop sign and stopping locations were added to the map for a single position. This was done ostensibly to avoid legal conflicts related to taking responsibility for defining the legal stopping location. Thus, both stop sign and stopping location data were coded into the map database based on actual posted stop sign positions and the locations of the stop line. In short, two locations were added to the map when just one will do. This is costly in terms of time and effort, and adds unnecessary cost to the map development process.

2.2.5.3 Stop Sign Ahead and Grade Mapplets

Stop ahead sign and grade mapplets were of little use. The application can generate stop ahead advisories on its own. Only when it is beneficial to the driver, such as for a stop sign at the end of a curved section should an advisory be issued. For this reason, information on road geometry would be beneficial.

Although road grade information was initially identified as a relevant mapplet for the SSA, it was not employed. Instead, the application was designed with real-time feedback to observe changes in speed and distance to the mapplet or object. In this way, the application increased or decreased brake level as needed without requiring grade information. However, grade information would be beneficial in places where grade is greater than 5% or under slippery conditions.

2.3 Forward Collision Warning

2.3.1 Introduction

GM developed and demonstrated the Forward Collision Warning (FCW) application using the mid-term map database and the Honeywell (lane-level) positioning system. Figure 2-15 shows the main modules of this application in the form of a simplified block diagram.

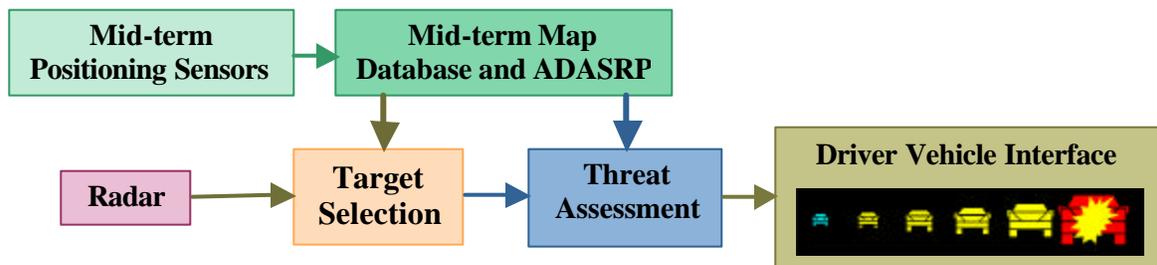


Figure 2-15: Forward collision warning block diagram

At the center of this map-enhanced FCW application is the radar sensor that identifies potential collision targets in its field of view. Key to the success of a radar-based FCW system is the correct selection of in-path targets, i.e., those that are in the expected future path of the host vehicle (no missed detection), and correct elimination of irrelevant targets, i.e., those not actually in the forward path of the vehicle (no false alarms). This is accomplished by determining the intersection of the identified radar targets with the upcoming road geometry. This makes the accurate and reliable prediction of host vehicle path an important and essential component of the FCW algorithm.

The primary maplet that supports FCW target selection is forward lane geometry. The target selection module uses other maplets to develop a valid look-ahead range by limiting upcoming path definition to an approaching stop sign, stopping location, or intersection in conjunction with vehicle speed. It uses the forward lane geometry, look-ahead range, the lane width maplet, and vehicle heading in lane for classification of radar targets as in-path or out-of path. In addition, the target selection module uses the overhead stationary roadway structures, stationary roadside objects, and the stationary roadside barriers maplets from the map module to reduce false alarms. This module provides the target IDs of closest in-path moving vehicle (CIPV) and closest in-path stationary (CIPS) radar targets to the threat assessment module.

The threat assessment algorithm uses the CIPV and CIPS obtained from target selection to calculate a threat level based on the kinematics of the vehicle and the radar targets. It also uses the road condition, road surface type, road grade, and road class maplets to adjust the threat level based on map information.

The threat levels and the FCW status (e.g., system inactive) are conveyed to the driver primarily via a visual interface (full-color, reconfigurable Heads-Up Display). Different sized and colored icons (shown in Figure 2-15) have been used to communicate the various warning stages, namely, vehicle detected (a small cyan-colored vehicle), cautionary (various sized amber-colored vehicles), and imminent warning (a large red-colored vehicle with a yellow-colored splash), as computed by the threat assessment algorithm. In the case of an imminent alert, the visual alert is accompanied by an auditory alert to provide the driver with a greater sense of urgency.

The FCW application (with the Curve Speed Assistant, the GM near-term application) was demonstrated and evaluated over a broad range of scenarios on selected routes in Palo Alto, California (17 miles long) and southeast Michigan (22 miles long) (Figure 2-16, detailed further in Section G.1 in Appendix G). In this figure, the freeway routes are shown in blue color, and include multiple lane freeways (with and without roadside barriers, namely, median walls and guard rails) and their associated ramps. These roads have no tree cover and typically did not present any satellite obscuration problems. The non-freeway routes mostly comprise single (at times two) lanes in each direction (shown in green and red colors in Figure 2-16). These roads have ample tree cover and presented many challenges to the lane-level positioning system, especially in the southeast Michigan region (roads depicted in red color in Figure 2-16). Apart from including the commonly encountered road types, namely, straight, curves and curve transitions, and freeway/arterial streets and ramps, these routes also include the scenarios where FCW applications generally exhibit poor performance, e.g., urban and curving roadways where objects (e.g., guard rails, mailboxes, etc.) are commonly placed within 2 m of the roadway edge, and areas where reception of GPS signals may be considered difficult due to overhead objects (e.g., overpasses, overhead signs, and bridges) and foliage.

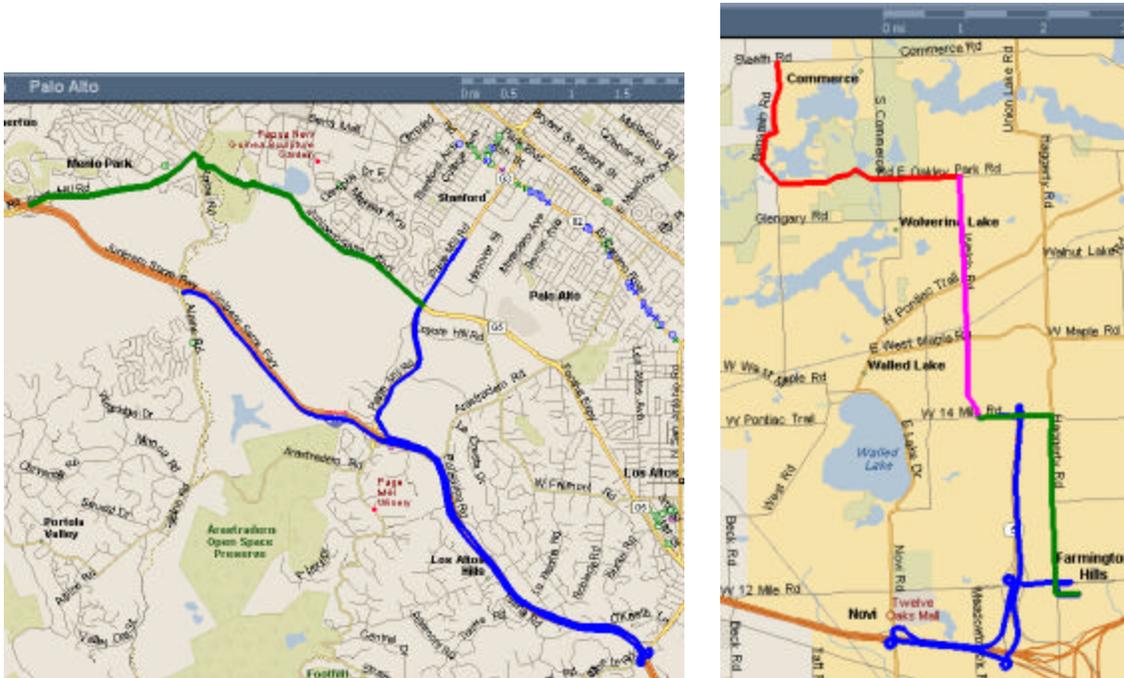


Figure 2-16: California (left) and Michigan (right) FCW demonstration and evaluation routes

2.3.2 Application Behavior

The FCW application uses lane-level positioning to determine the lane in which the host vehicle is traversing on the roadway and extracts pertinent information regarding that lane from the mid-term map database, using ADASRP. It uses the predicted upcoming lane geometry in conjunction with the radar targets and identifies the closest in-path target. This implementation of FCW relies on the accuracy of the estimation of the vehicle position to the correct lane and the accuracy of the upcoming lane geometry to predict the forward path of the host vehicle because it assumes that the geometry of the current lane will be the future path driven by the vehicle. As long as the lane-level map and positioning system together have no more than one-half lane width of error, the FCW is presented with the correct forward path preview by the ADASRP. An example of a correct lane-level preview is shown in Figure 2-17a, where the host vehicle is positioned in the “exit only” lane and the primary path geometry returned by the ADASRP comprises the preview of the upcoming ramp.

2.3.2.1 Correct Target Selection / Correct Target Rejection

The ability of selecting a correct in-path target in terms of the acquisition time as it moves into the host vehicle lane and the release of a target as it moves out of the host lane is critical to the proper functioning of FCW both from a safety and user acceptance perspective. In addition to making correct decisions regarding in-path targets, it is equally important to reject targets that are out-of-path such as those present in adjacent lanes or along the roadside such as roadway signs and barriers in order to reduce false target detection. This is important for improving the user acceptability.

Figure 2-17a highlights the benefit of the lane-level preview because it enables the correct choice of the in-path target (target #5) as soon as the vehicle is positioned in the lane that leads up to the ramp, well before the host vehicle is mapped onto the exit ramp. In contrast, if the application had relied on road-level preview for target selection, the ramp geometry is provided as the upcoming preview only when the vehicle gets unambiguously mapped onto it (generally occurs 40 to 50 m into the ramp). During this period, the correct target (target #5) would be ignored (resulting in a missed detection), and in some cases, an incorrect target could potentially be selected as an in-path target (false detection).

Figure 2-17b shows an example of proper target selection and rejection during a case of an upcoming road curve. Here, two in-path vehicles (targets #1 and #7) are correctly placed in the host vehicle path, and the vehicle in the oncoming lane (target #3) and other radar clutter (target #5, #8, and others) get correctly placed outside the upcoming path of the host vehicle.

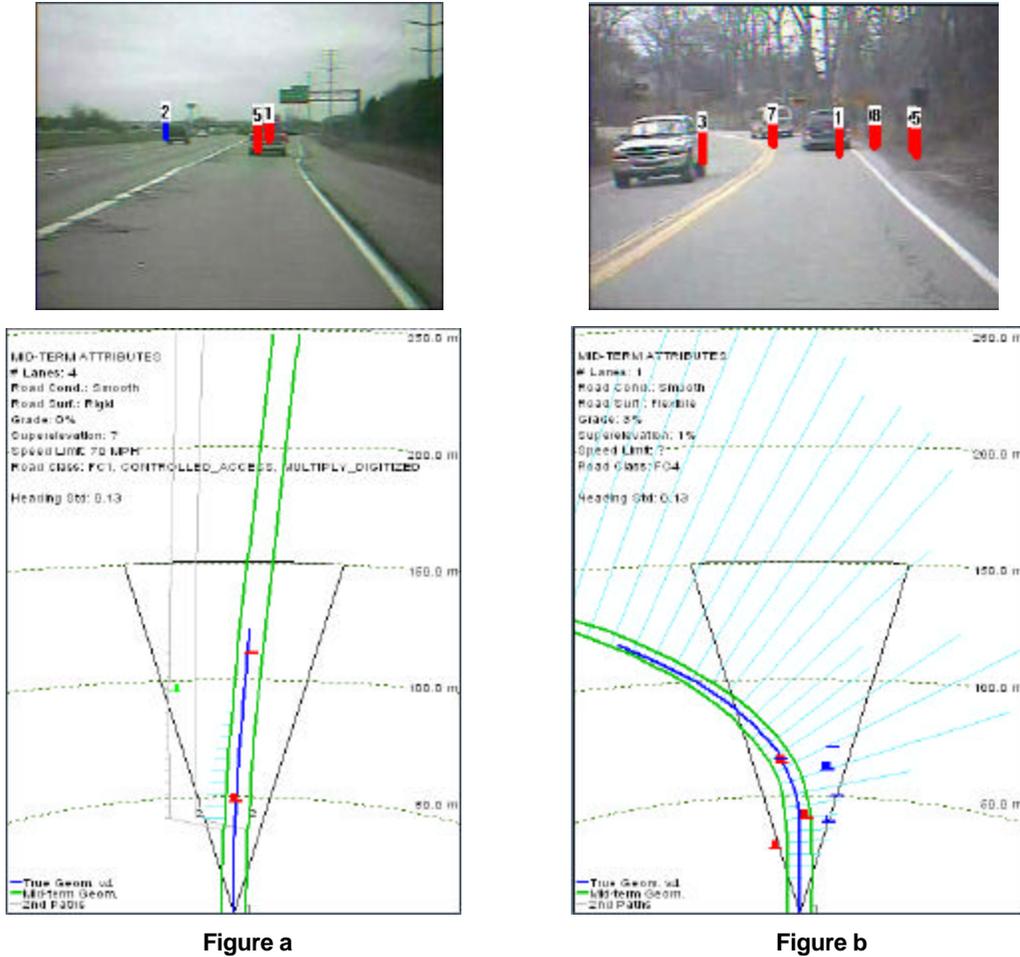


Figure 2-17: Correct target selection and correct target rejection

2.3.2.2 Incorrect Target Selection (False Detection) / Incorrect Target Rejection (Missed Detection)

Incorrect target selection has a detrimental effect of potentially presenting the driver with nuisance alerts, thereby reducing the overall user acceptability of the FCW system. Figure 2-18a (top) shows the case of a guard rail placed in close proximity of the lane that the vehicle is currently traversing. Here, several of the returns received by the radar from the guard rail lie within the upcoming lane geometry provided by ADASRP as shown in Figure 2-18a (bottom). After processing these radar returns in conjunction with the upcoming lane geometry, the target selection algorithm incorrectly selected target #4 (false detection), as an in-path target and passed it on to the threat assessment algorithm for further review.

Incorrect target rejection or missed detection presents the most undesirable scenario and has the potential of resulting in a collision with the missed target. Figure 2-18b shows an example of an incorrect target rejection (or missed detection) using the lane-level preview provided by ADASRP. Figure 2-18b (top) shows the scenario of an upcoming straight lane with a target vehicle (target #1) in the host vehicle path. As seen from Figure 2-18b (bottom), the lane-level preview provided by the ADASRP when compared to the output of the post-processed ground truth (blue colored line) appears to be incorrect. Figure 2-18b (bottom), shows the lane geometry

jog to the right in the proximity of the upcoming intersection (thin green lines), thereby missing target #1 and yielding a missed detection.

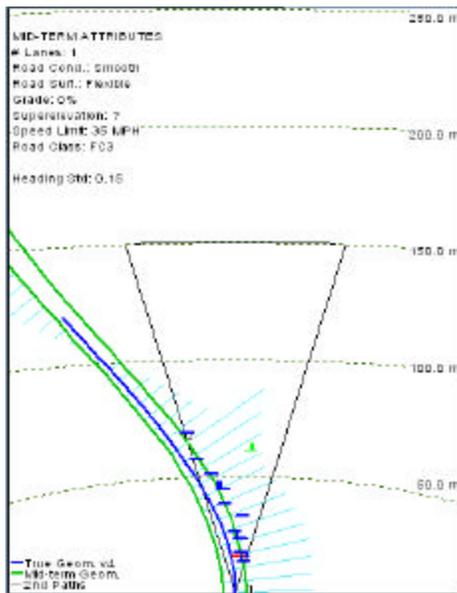
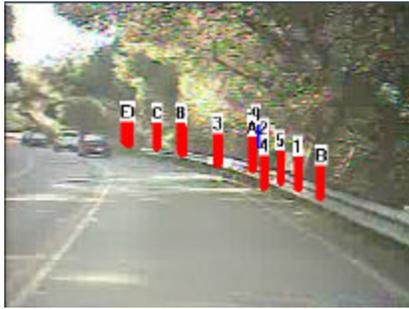


Figure a

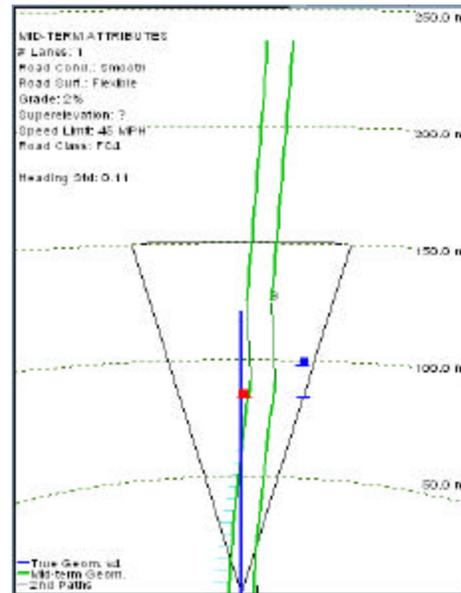


Figure b

Figure 2-18: Incorrect target selection (a) and incorrect target rejection (b)

2.3.3 Application Evaluation

This section provides the results of the map-based FCW application evaluation with emphasis on the role of maps in the target selection module (additional details on the FCW application evaluation are presented in Section G.3 in Appendix G). The results are presented by evaluating the map-based target selection against two other sources. The first comparison target selection algorithm is the yaw rate-based algorithm contained in the forward-looking radar (also known as radar-based target selection) and primarily used for adaptive cruise control applications. The other comparison is the same target selection algorithm used with the map-based data but using the GM-developed ground truth³ (see Section G.2.1 in Appendix G, *FCW Evaluation*, for details) instead of the map.

³ GM developed ground truth defines the actual path driven by the vehicle and is derived by post processing logged vehicle speed and yaw-rate measurements.

Logged data from the CA and MI demonstration routes, where the vehicle speed was greater than 25 mph (FCW application specification), was processed to derive files comprising records each containing the EDMap-based closest in-path vehicle (CIPV), EDMap-based closest in-path stationary object (CIPS), yaw rate-based CIPV, and ground truth based CIPV for each instance where the targets selected by the EDMap-based, yaw rate-based, and ground truth based target selection differed. In addition, a count of the number of times that the three methods agreed was maintained.

The records produced in this way were then validated by inspection of logged data using the GM developed visualization tool (described in Section G.2.3 in Appendix G). For each record, the reason for the discrepancy was determined and a score of either a correct or incorrect was assigned to the columns EDMap and Yaw rate according to whether the decision was judged to be correct or incorrect, respectively. Table 2-6 tabulates these results in terms of percentages of the total records. For example, the last cell in the first row of this table shows that the EDMap-based and the yaw rate-based target selection yielded incorrect results (either missed a target or selected an incorrect target) in 1.2% of all instances in the CA and MI evaluation routes.

Table 2-6: Scores of EDMap-based versus yaw-rate-based target selection

Row #	EDMap	Yaw-rate	CA	MI	Total
1	Incorrect	Incorrect	1.3	1.1	1.2
2	Incorrect	Correct	2.1	1.7	1.9
3	Correct	Incorrect	9.8	19.5	14.4
4	Correct	Correct	87.0	77.6	82.5
5	#Records with vehicle speed > 25 mph		7759	7179	14938

Table 2-6 shows that:

- A fairly large sample size of approximately 15,000 records was evaluated at both the CA and MI test sites to study the usefulness of EDMap for FCW applications.
- Overall, the EDMap-based target selection outperformed the yaw-rate based target selection by approximately 13% in all instances.
- In a majority of the instances (over 82%, row #4 in Table 2-6), the EDMap-based and the yaw rate-based target selection both agreed with each other and selected the correct target. It is reassuring to note that the EDMap-based method agreed overwhelmingly with the yaw rate-based target selection results because yaw-rate based target selection has traditionally proven to be a very accurate predictor of road geometry under conditions of constant curvature (straight and curved roads).
- A significant value added by maps was observed in 15% (row #3 in Table 2-6) of the total cases, where the EDMap-based target selection consistently selected the correct targets while the yaw rate-based target selection either selected an incorrect target or missed a target. This observation is attributed to the fact that although the yaw rate-based road curvature prediction has proven to be an excellent source of local road shape through the vast majority of the driving experience, it is a very poor predictor in the presence of upcoming road curve

transitions (curve entry and exit scenarios), during host vehicle lane changes, and it degrades significantly at low host vehicle speed.

- Of the total records, there were very few instances (around 1.2%, row #1 in Table 2-6) where both EDMap-based and yaw rate-based target selection were incorrect.
- A detrimental effect of using maps for target selection was observed in a small percentage (approximately 2%, row #2 in Table 2-6) of the total records when the yaw rate-based method selected the correct target while EDMap-based target selection either selected an incorrect target or missed a target. These instances are attributed to the cases of inaccurate path geometry, and when the distance to the target was over 120 m (EDMap limits look ahead range to 120 m, while the yaw-rate based and the ground truth based target selection are at times able to classify targets at ranges greater than 120 m).
- Of the 3.1% of the total instances where the EDMap-based target selection made an error (rows #1 and 2 in Table 2-6), 1.31% were due to false detections and 1.75% due to missed detection. Overall, the percentage of missed detection was found to be higher than the false detection and is attributed to the cases where the distance to the target is over 120 m and to inaccurate path geometry (note that inaccurate path geometry also influences false detection).

2.3.4 Maplet Evaluation

This subsection presents the results of the evaluation of all the maplets that were used in the implementation of the FCW application. Additional details of the evaluation of maplets used for this application are presented in Section G.4 in Appendix G.

2.3.4.1 Lane Geometry

The FCW application depends on the accuracy of the lane-level geometry (specified at 0.5 m) for a range of 120 m ahead of the host vehicle (see Appendix B, Sections B.3 and B.4 for details). To assess the accuracy of the lane-level geometry, the difference between the lane geometry furnished by the ADASRP and the GM developed ground truth (see Section G.2.1 in Appendix G, *FCW Evaluation* for details) has been computed. To allow the ease of comprehension of the results, this difference has been computed and summarized at two discrete preview distances of 60 m and 120m from the host vehicle. The 60 m preview represents the distance corresponding to a 3-second headway at speeds of 45 mph seen on most arterial roads encountered in suburban driving, and is relevant for the FCW application. The 120 m preview distance is selected because it is important to evaluate the accuracy of the lane geometry at the maximum range for which the FCW application is specified to operate.

Table 2-7 depicts the mean error and its standard deviation observed for the CA and MI evaluation trips at the 60 m and 120 m preview distances. As expected, the results obtained for a 60 m preview distance are better than those obtained for the 120 m preview distance. The overall mean obtained by considering both the CA and MI evaluation files is 0.25 m for the 60 m preview distance and 0.75 m for the 120 m preview distance.

Table 2-7: Mean error and its standard deviation for the CA and MI evaluation trips

Error	CA		MI	
	60 m	120 m	60 m	120 m
Mean	0.07	0.14	0.44	1.47
Standard Deviation	4.32	9.86	4.33	11.24

Next, the error in lane geometry for the CA and MI evaluation routes was separated into 3 different bins of the following sizes:

- Error <0.5 m, to capture the percentage of total instances when the lane geometry met the accuracy specification of 0.5 m.
- Error >1.75 m, to capture the percentage of instances when the lane geometry had an error of over half a lane width (Assumption: a typical lane is 3.5 m wide).
- 0.5 m < Error < 1.75 m, to capture the percentage of total instances when the lane geometry had an error greater than 0.5 m but less than half a lane width.

For the CA and MI evaluation files, Table 2-7 depicts the error distribution in the three bins for the 60 m and 120 m preview distance and shows that the overall accuracy of lane geometry deteriorates with preview distance. At the 60 m preview distance, the percentage of total instances that meet the specification of 0.5 m error is 28% as compared to the 16% for the 120 m preview distance. Table 2-7 also shows that for a 60 m preview distance, 65% of all instances exhibit an error of less than half a lane width, while for the 120 m preview distance less than 47% of all instances are within an error of less than half a lane width.

Table 2-8: Error distributions at 60 m and 120 m preview distances for the CA and MI Trips

Error bins	60 m Preview Distance			120 m Preview Distance		
	CA	MI	Total	CA	MI	Total
Error < 0.5 m	21	37	28	12	21	16
0.5 m < Error < 1.75 m	40	33	37	28	35	31
Error > 1.75 m	39	30	35	60	44	53
# Samples	16900	14179	31079	16900	14179	31079

Although the overall accuracy of the lane geometry seems to deviate from the specification of 0.5 m for a significant portion of all instances (Table 2-7), it was found to work satisfactorily for the FCW application (as discussed in Section 2.3.3 where EDMap chose the correct target over 95% of the time). The seemingly large errors in the lane geometry can be attributed to the fact that the evaluation files contain a significant number of lane changes, which yield large differences, and therefore error, between the EDMap predicted lane geometry and the ground truth. This mapplet is useful to the FCW application and it is recommended that this mapplet at the originally specified accuracy be included in future lane-level map databases developed for this application.

2.3.4.2 Lane Width

The implementation of the target selection module utilizes a fixed lane width of 3.5 m to decide if a target in its forward view is in-path or not. In general, making the lane too wide invites false alarms by including targets from adjacent lanes (or from the roadside) that do not necessarily pose a collision threat.

Evaluation files logged during the MI tests were reanalyzed using the lane width information populated in the mid-term EDMap databases. It was observed that the results of the target selection module were nearly the same as those obtained using the fixed lane width of 3.5 m. A review of the EDMap lane widths used in the reanalysis revealed that nearly all the populated lane widths were larger than the 3.5 m originally used in the test vehicle. Thus, the target vehicles registered as in-path using the constant 3.5 m lane width continued to be assigned as in-path targets using the EDMap lane widths. Few instances were found in which using the generally larger path widths furnished by EDMap degraded the target selection performance.

It is concluded that the benefit of including the lane width in the mid-term database is marginal, if any, for the FCW application and it is therefore recommended that this maplet be deleted from the original maplet set specified for the FCW application.

2.3.4.3 Road Class

Road classification is useful to initiate, inhibit, and resume FCW operation based on the class of roads (e.g., controlled access or ramps) that are being negotiated by the host vehicle. It is believed that this maplet as defined in the current production navigable databases is sufficient and recommend that it be retained in future map databases developed for this application.

2.3.4.4 Intersection Location

This maplet is useful to adjust the look-ahead range when used in conjunction with host vehicle speed (only when the host vehicle is decelerating) to reduce confusion caused by radar targets moving perpendicular to the host path. This maplet holds potential for reducing false alarms that can be caused due to cross traffic. It is recommended that this maplet be retained in the future map databases developed for this application with a relaxed accuracy of 10 m.

2.3.4.5 Overhead Stationary Structures

The forward-looking radar in the FCW system can detect overhead structures as in-path objects. The California evaluation route included only one overhead bridge while the Michigan route had two. These overhead structures were typically encountered when the vehicle was traveling on a flat road surface, and therefore these structures did not yield any radar returns that constituted in-path targets. Due to the absence of a sufficient number of overhead stationary object maplets on roads that exhibited grade changes in the EDMap mid-term evaluation routes, the effect of this maplet on the FCW application performance could not be evaluated. However, this maplet is important to reduce the false alarms produced from radar targets obtained from overhead structures encountered on graded roads. It is recommended that this maplet be included in a mid-term map database.

2.3.4.6 Stationary Roadside Barriers

The EDMap demo routes, both in California and Michigan, had a number of false alerts from guard rails and other roadside barriers. This maplet was not consistently present in the Michigan or the California map database. Based on analysis of the instances where this maplet was available in the Michigan map database, it has been concluded that the maplet is useful and

improves the FCW application performance by reducing some of the false alerts from guard rails placed in close proximity to the road edges. It is recommended that only roadside barriers within 2 m of the outer travel lane be retained in the mid-term map database.

2.3.4.7 Road Condition

This maplet was not used by the FCW application and its effect on the FCW application performance has not been analyzed. However, at the present time, the benefit of using this maplet is not obvious, and it is therefore recommended that this maplet be deleted from the mid-term map database specification.

2.3.4.8 Road Surface Type

This maplet was not used by the FCW application and its effect on the FCW application performance has not been analyzed. Road surface type classification of paved or unpaved can be used to improve the FCW application performance, and therefore it is recommended that only two classification types for this maplet be included in future databases: paved and unpaved.

2.3.4.9 Road Grade

The effect of road grade on the FCW application warning timing was not evaluated to date. It is important that the FCW system use road grade information and adjust the warning time of the alert to the driver appropriately. At the present time, the original requirements of an accuracy of $\pm 2\%$ grade in discrete values of 2% would be beneficial. Further analysis of the road grade information from the map database and its effect on alert timing will be required (beyond the scope of this project) to revise the original requirement.

2.3.4.10 Stationary Roadside Objects

This maplet was not present in the EDMap mid-term database and so its effect on the FCW application performance could not be evaluated. At this time, the benefit of this maplet as currently defined appears to be marginal (the collection of this maplet is very subjective), and it is therefore recommended that it be deleted from the mid-term map database.

2.3.5 Vehicle Positioning Performance and Analysis

This implementation of FCW primarily utilizes lane geometry to predict the forward path of the host vehicle because it assumes that the geometry of the lane will be the geometry driven by the vehicle. Although all lanes run parallel to one another most of the time, there are many instances near intersections when this is not the case. Because of this and the assumption FCW makes, the least flexible requirement for lane-level map matching requires the map and positioning system together to have no more than one-half lane width of error, or approximately 1.8 m error. A greater error causes greater lane uncertainty, which can result in incorrect forward geometry.

The work performed in Task 2 yielded map and positioning requirements of 0.5 m accuracy (see Appendix B, Section B.3 for details). Throughout this task, it has been determined that correct lane matching is critical for the proper functioning of this application especially in the proximity of road bifurcations. For this reason, the following analysis will focus on accuracy requirements resulting in correct lane matching using the Honeywell lane-level positioning system described in Section 4.3.1. The three main areas contributing directly to the positioning performance (and therefore lane matching) are the number of observable satellites, the obscuration of satellites due to tree cover and overhead bridges, and the availability of carrier-phase differential corrections.

2.3.5.1 GPS Constellation

The GPS constellation plays an important role when estimating the number of satellites a GPS receiver will be able to track at any time. To resolve position and time issues, a GPS receiver needs measurements to four GPS satellites. As the number of observable satellites increases while performing basic positioning, the GPS receiver can optimally choose the satellites to include in the solution in order to increase the accuracy. For carrier-phase differential GPS positioning like that performed for lane-level positioning, the GPS receiver can use multiple measurements to satellites to decrease the time to solve for ambiguities in the position solution. In theory, the net result of more satellites in view is a better position in a shorter time. Figure 2-19 shows that although the overall positioning does appear to be improved by an increase in satellite observations, investigation into positioning performance did not show an appreciable difference over time as the satellite constellation improved.

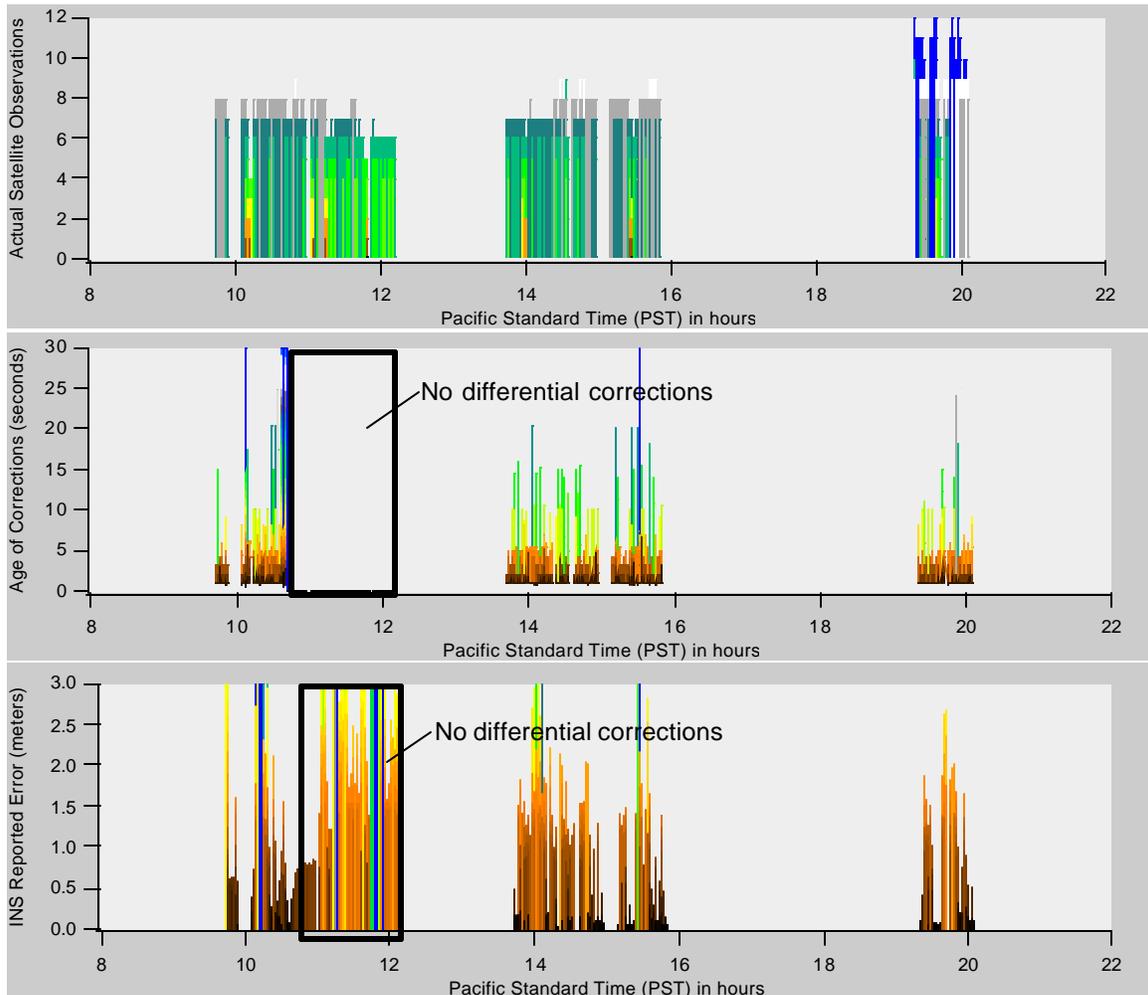


Figure 2-19: INS performance during day one of California demonstration

2.3.5.2 Availability of Differential Corrections

Carrier-phase differential corrections are required by the GPS receiver to achieve lane-level (sub-meter) positioning accuracy. Figure 2-19 shows that as the age of differential corrections increases, the INS self-reported standard deviation of error increases thereby reducing the value of the corrections to the positioning solution. The figure illustrates that large spikes in the age of differential corrections yielded larger positioning errors, and very few instances of positioning accuracy being better than 3m were observed when carrier-phase differential corrections were absent. Availability of differential corrections has a direct impact on positioning performance and likely has a direct impact on map-matching performance.

2.3.5.3 Satellite Obscuration

While a ground vehicle is traveling on a roadway, items such as signs, trees, or bridges may pass between the line of sight from the GPS satellite and the vehicle's GPS antenna. When this happens, the GPS receiver may lose its track on one or many GPS satellites, which can only result in degraded positioning performance or loss of position solution. The California demonstration and evaluation route exhibits a wide range of environments from clear open sky atop a hill to roadways heavily covered by tree foliage. For this reason, the trips taken by the demonstration participants provide a good data set for analyzing positioning and map-matching performance in a geographic sense.⁴

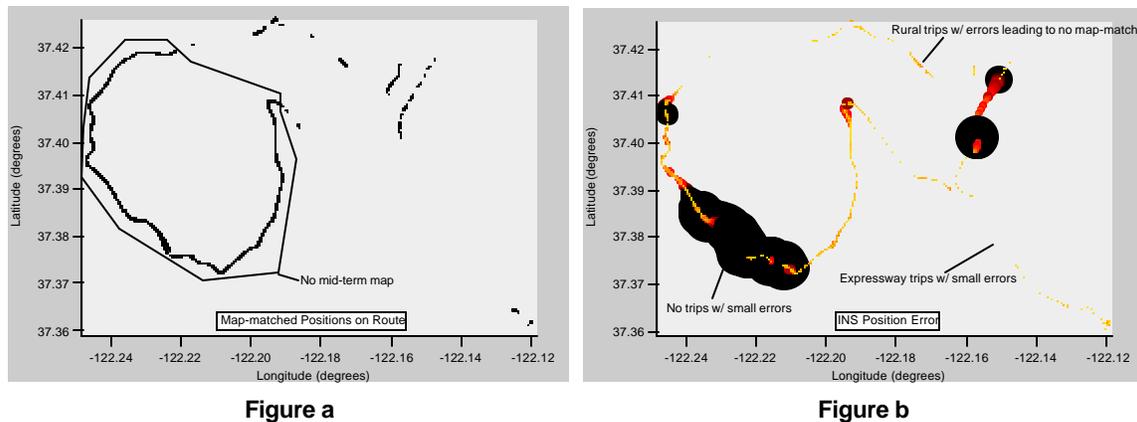


Figure 2-20: Position errors for multiple trips on the California demonstration route

Figure 2-20a shows the entire demonstration route in geographic coordinates. The darker colored points are locations where no map-match was made to the mid-term map database. The southwest corner of the map contains no mid-term map database and results in no lane-match possible for this region. Figure 2-20b shows the INS's self-reported position error in geographic coordinates on the demonstration route. Lighter, smaller samples are points where the INS reports small errors in positioning. As the positioning error increases, the points become darker and grow in size. The largest points on the graph correspond to 10 m of positioning error while the smallest points correspond to zero positioning error. For both of these figures, data from multiple trips by multiple participants is simultaneously displayed.

⁴ During one of the demonstration participant's drive, carrier-phase differential corrections were not available. For this reason, the data from this drive is not included in this analysis.

As can be seen in the two figures, the expressway portion of the route located in the southeast corner and heading towards the center of the figures yields good positioning performance and consistent map matching. Rural portions of the route experience small segments where positioning errors are greater and a few instances of no map matching occur. The difference between the performances is due to overhead tree cover. The expressway portion has no overhead tree coverage and consists of very few objects obstructing the view of the sky. The rural portions have intermittent groves of trees that prevent the GPS receiver from tracking certain satellites for the periods of time required for a high accuracy solution.

In the extreme case of tree coverage, the southwest corners of the figures show a region with very poor positioning performance. Had this region been mapped, it is doubtful the positioning system would perform well enough to match the vehicle to the appropriate lane. For lane-level maps to be useful in these types of regions, the vehicle must be equipped with a more reliable positioning system.

2.3.6 Possible Deployment Options and Potential Safety Benefits

The results of this project indicate that when the lane-level maplets were delivered to specified requirements and the Honeywell system provided reliable positioning data, the developed EDMap-based target selection application was superior to the traditional yaw rate-based target selection. However, the accuracy and reliability of the lane-level maplets and the positioning performance was not reliable at all times. For example, the performance of the lane-level positioning system was satisfactory under open sky conditions but suffered significantly under foliage. In addition, the lane-level maps and positioning systems are not cost viable at the present time. Based on the assumption that these issues will not be resolved in the immediate future, several potential deployment options of a map-based FCW system are outlined in this section.

2.3.6.1 Map-aided Yaw Rate Based Target Selection

As stated earlier in this section, the currently deployed FCW and ACC systems are yaw-rate based, and operate without any help from a map database. It appears that a map-aided yaw-rate-based system may have the potential to improve upon a yaw rate only system through scenarios that limit its operation such as during curve entry and exit scenarios. For example, a multi-sensor based target selection system can choose to reduce its reliance on the yaw-rate based subsystem for forward geometry prediction or limit its look ahead distance when the map indicates the presence of an upcoming curve. Even if the quality of the map is not sufficient to define the geometry of the upcoming road, it is able to reliably detect the presence of road transitions. Also, confusion caused by radar targets moving perpendicular to the host path can be potentially reduced if the target selection module is provided with knowledge of an upcoming intersection from the map database. Even if information regarding road intersections is not explicitly stored in the map database, it can be easily inferred.

2.3.6.2 Yaw Rate Aided Road-level Map Based Target Selection

Although not investigated in this project, with very reliable road geometry information and precise yaw rate sensors, a fused FCW system could enhance a yaw-only system. This would extend the reliability and the usability of the system especially through curve transitions. It can be expected that a precise road geometry maplet will be available sooner than precise absolute lane geometry maplet and therefore this implementation will potentially enhance the system functionality in the near-term to mid-term time frame. Currently, the roadside barriers and stationary roadway structures maplets have been implemented as lane-level maplets. These maplets are useful for target selection and can be moved to the road-level (WhatRoad) map databases. If it is determined that the accuracy of the road-level map would be sufficient for the

FCW application, additional schemes will have to be developed to resolve preview ambiguities that arise because the driver intent is unknown in the proximity of a bifurcation. Potential solutions include employing a routing mechanism that conveys the driver intent to the application, which comes with a disadvantage of added cost or may have to be limited to only those vehicles equipped with a navigation system.

2.3.6.3 Road-level Plus Lane-level “Hybrid” EDMap-based Target Selection

Under the current project, the FCW application has been implemented as a lane-level application. It relies on the accuracy of the estimation of the vehicle position to the correct lane and is not sensitive to errors in the measurement of the position within lane, thereby making it a WhichLane application. Here, a greater burden is placed on the correct placement of the vehicle in its appropriate lane in the proximity of intersections, because in most other circumstances lanes on the roadway run parallel to one another and are expected to yield a similar lane preview, even if the vehicle is erroneously placed in an adjacent lane. Since the application can tolerate errors in the placement of the vehicle to the correct lane a meaningful deployment option is to use a “hybrid” map consisting of a road-level map when lanes run parallel to one another (in such situations a lane-level map is not needed) and a lane-level map when preview ambiguities exist in the proximity of intersections and other bifurcations. Such maps must be employed in conjunction with a lane-level positioning system (to allow the correct placement of the vehicle in the proximity of bifurcations) whose performance is affected by satellite visibility, DGPS outages, and availability of ubiquitous carrier phase differential corrections.

Initial estimates of the cost of developing a database to support this application at the accuracy, maplet, and coverage levels were quite high compared to the current navigation grade databases. However, since the FCW application is specified to be operational over 25 MPH, it obviates the need to develop the map databases for the low speed neighborhood roads which constitute over 75% of the total map coverage area. According to a NHTSA report [1], rear end crashes constitute about 29% of the total vehicle crashes (there were 6,133,000 light vehicle police-reported crashes in 2000). Approximately 8% of these rear end accidents occur on roads with posted speed limits of 25 MPH or lower, and account for about 7% of all costs incurred in such crashes. Based on these facts, if the FCW application is confined to operate on roads with speeds of 25 MPH or higher, an overall 8% reduction in the potential safety benefits (as identified in Task 1 of the project, see Appendix A for details) is expected. Note that although 8% of such accidents occur on roads with posted speed limits of 25 MPH or lower, they have substantially smaller number of fatalities or serious injuries due to the low host vehicle speeds.

2.3.7 References

[1] Najm, W.G., "Frequency and Severity of Rear-End Crashes by Travel Speed of Striking Light Vehicle". HS-16, Volpe National Transportation Systems Center, U.S. Department of transportation, Cambridge, MA, May 2003

2.4 Traffic Signal Assistant

2.4.1 Application Performance and Results

The goal for the Traffic Signal Assistant (TSA) is to reduce red light violations by warning a driver if the vehicle approaches a red light without any indication of stopping. Therefore, the application can be divided into two components:

- Detection of the signal indication
- Generating a warning to the driver when a red light violation is imminent

The application is based on a lane-level map and utilizes the Honeywell PAPS sensor for positioning. The traffic signal location and stopping location maplets reported by the map are used by the system. The detection of the traffic signal indication uses a color camera system as a primary sensor that is aided by the traffic signal location reported by the map. The warning portion of the application is very similar to a stop sign warning once a red light is detected. The algorithm is configured such that if the driver does not slow down and a deceleration of at least 0.4 Gs is needed to stop the vehicle at the stopping location after a reaction time of 1.0 second, an audible warning (“*Stop, red light!*”) is issued to the driver. For demonstration purposes, the system also announces when the signal indication is detected:

- Green – “*Green light ahead.*”
- Red – “*Red light ahead.*”

This user interface is obviously not what would be used in a production version; nevertheless, it illustrates the functionality and status of the application very well. The main advantage of the map for this application is in aiding a vision system to detect the signal indication relevant for the lane the vehicle is traveling in.

Overall, the application performs well. Generally, the detection of signal heads and the corresponding indication can be done very reliably with a stand-alone vision system. Signals at complex intersections, however, represent a challenge since it is not necessarily obvious which signal heads control the lane the vehicle is in, especially when the road approaching an intersection is curved. As demonstrated, the Traffic Signal Assistant successfully manages (in most cases) to identify the correct signal indication in complex intersections by focusing on the signal locations and status (control/no-control for the current lane) reported by the map (see Figure 2-21; yellow boxes indicate signal heads controlling the lane the vehicle is in). The search boxes are 3m wide and extend from 1.5 m above the horizon to 7m above the horizon. The projection of the search boxes takes the vehicle GPS position, the signal head GPS position, vehicle heading, and camera offset from the GPS receiver into account. The search box size was determined experimentally and proved to be the smallest size the application could comfortably tolerate at the given map accuracies and expected GPS errors. Limiting the search to the search boxes also allows the increase of the sensitivity of the vision system.

The full screen “reference” system that was used to evaluate the performance of the map uses a search area that extended from the horizon in the camera image to the top of the image. In addition, the two systems were only evaluated near signal-controlled intersections. False alarms given by the full-screen system due to other influences during normal driving away from signal-controlled intersections were not evaluated. This, in turn, reveals a finding that even a full screen vision system can benefit from a road-level map that simply reports signal-controlled intersections.

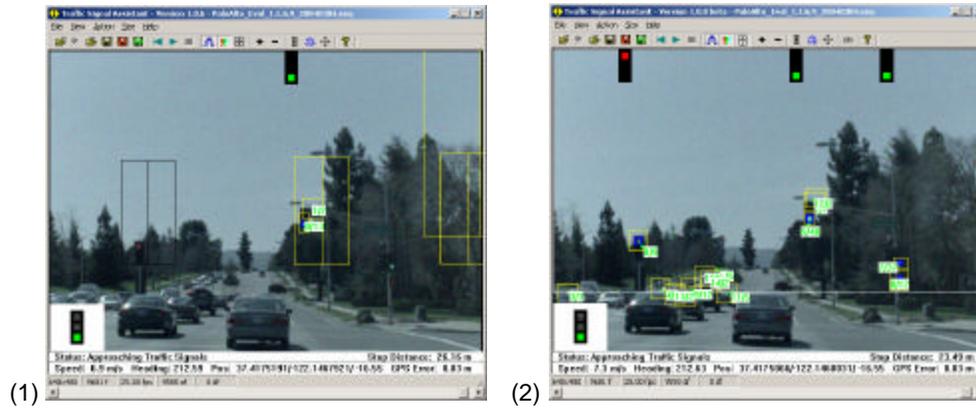


Figure 2-21: Control/no-control signals

- (1) Correctly identified signals controlling the traveled lane (search limited to search boxes)
 (2) Full screen search identifies both straight and left turn signals

One of the challenges that the Traffic Signal Assistant faces is that it is not able to reliably detect a yellow signal indication. Frequently, yellow traffic signals were not correctly detected, and sometimes they were identified as red signals, which can actually be beneficial since a yellow signal indication, which will therefore change to red soon, can be used to initiate the stop warning algorithm. However, the detection achieved within the scope of this project was not reliable enough to enable this in the demonstrated application. A production system would have to use an improved vision algorithm in order to detect a yellow indication reliably.

Furthermore, heavy rain and snow, fog, sun, and sun glare will greatly influence the vision system performance. During the California application demonstration, sun was the culprit for most of the vision system misbehaviors. Depending on the time of day, signals were missed or misidentified due to sun reflections on the lenses or reflections off other objects in the search boxes. This is particularly true for east/westbound roads in the morning and evening, respectively, and presents a limitation on vision systems in general.

The stop warning portion of the system performs very well in locations where the stopping location at the intersection is mapped accurately enough, and a red signal indication is correctly identified by the vision system component. It should be pointed out that the TSA needs the accurate mapping of both the signal location and the stopping location to function properly.

2.4.2 Maplet Analysis

Figure 2-22 shows the TSA demonstration and evaluation routes in both Palo Alto, California and in Farmington Hills, Michigan. The locations of signal controlled intersections are numbered according to the order in which they are passed as one drives along the respective route. Overall, there were 34 signal-controlled intersection crossings on the Palo Alto demonstration route. Locations 1-6 and 25-34 (segment 1) are located in a relatively open area. Locations 7-24 (segment 2), on the other hand, are located on a road with heavy tree cover. The differences and positioning performance in the two segments are discussed in section 0. Most of the intersections on the California route were complex intersections with turn lanes (mostly left turn lanes), making it particularly challenging for the vision system to detect the correct signal indication for the lane the vehicle was traveling in. In the Michigan area, the Traffic Signal Assistant was evaluated on a route that included 14 signal-controlled intersection crossings.

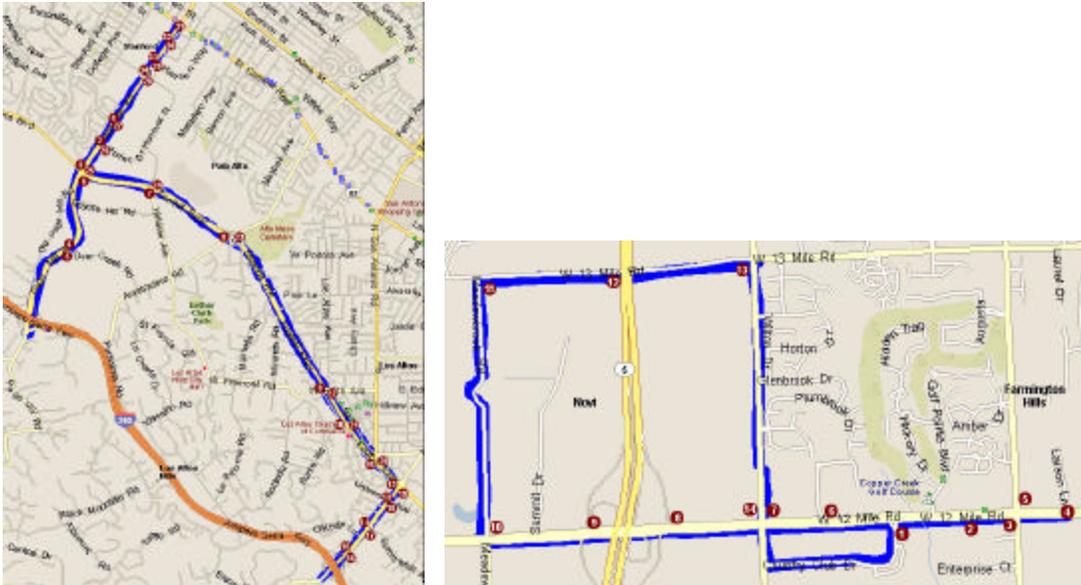


Figure 2-22: Traffic Signal Assistant evaluation route in California and Michigan

2.4.2.1 Stopping Location Maplet

The stopping location maplet accuracy varies greatly which, in turn, influences the system performance. In the evaluation process, each stopping location was measured and evaluated by stopping at the stop line and determining the offset of the map from the ground truth using the Honeywell PAPS positioning system. Figure 2-23 shows the distribution of offsets measured for the intersection crossings in the California and Michigan area. The numbers are absolute values and do not reflect the fact that in a few instances the offset was negative, meaning that the position of the stopping location in the map was ahead of the intersection which would result in a premature warning. Also, stoplights, which were mapped and did not have a corresponding stopping location mapped in the database (6 instances), were not considered. The mean and standard deviations (somewhat tenuous due to limited sample size) were 4.9 m and 4.8 m respectively. If the largest outliers in the data were eliminated (anything above 10 m), then the mean and standard deviation was 3.5 m and 2.3 m respectively. This is significantly larger than the original requirement of 1 m error and even somewhat larger than the relaxed requirement of 3 m, discussed below. It is instructive to note that only 18 out of 47 traffic signals were within the relaxed requirement.

Since the Traffic Signal Assistant only issues a warning and does not actually stop the vehicle, the accuracy of the stopping location is not as critical as in a controlled vehicle. Nevertheless, during the test evaluation and demonstration drives, a stopping location less than 3 m from the ground truth would generally give the driver a good warning and enough time to stop the vehicle before entering the intersection. A reported stopping location between 3 to 5 m ahead of the intersection would give the driver the impression of a premature warning. A stopping location reported more than 5 m ahead of the intersection would cause an early warning and can be viewed as a false warning, where the driver can easily brake normally or even lightly to stop at the stop line.

On the other hand, a stopping location between 3 to 5 m behind the actual stop line would give the driver a slightly late warning, and heavier than normal braking would be needed to stop the vehicle at the stop line. A stopping location more than 5 m behind the intersection would give the driver no warning or a very late warning that is not acceptable and does not allow the driver to stop the vehicle in time.

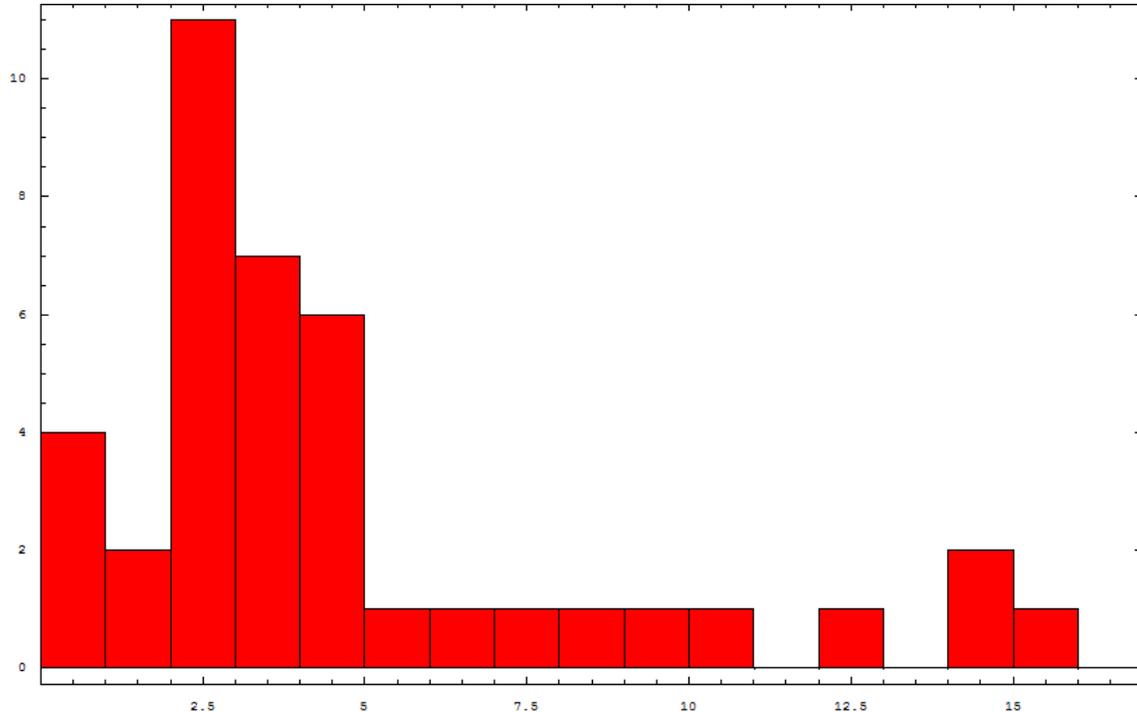


Figure 2-23: Distribution of stopping location errors in CA and MI

2.4.2.2 Traffic Signal Location Maplet

The number and status (controlling/non-controlling) of signal heads reported at all intersections in the evaluation areas were analyzed first. In California, there were 133 signal heads along the evaluation route that were relevant to the application. Overall, there was one error of omission and one error of commission in the Palo Alto map database. The missing/additional signal reported by the map had no impact on system performance. This is largely due to no intersection missing all signal heads and due to redundancy of signal heads at intersections. In the case of one intersection (out of 34), the map reported all eight signal heads as controlling the through lane, where four of those signals were actually left turn signals mislabeled in the map database. On the Michigan evaluation route, on the other hand, all signal heads (a total of 35) were correctly reported by the map database.

The signal head positional accuracy was very difficult to determine due to the missing ground truth. It is, however, the most critical component in the TSA system since it directly influences the area of the camera image on which the vision system portion of the system will concentrate on to determine the signal status. During the tests, it was found that a signal indication had to be detected at least 50 m from the stopping location at the intersection in order to give the driver an adequate warning. It is desirable to know the signal indication at approximately 80 m from the stopping location. This distance is dependent on vehicle speed; however, anything closer than 50 m would not allow the system to produce an acceptable warning, even at speeds as low as 25 mph. Therefore, it was manually evaluated (based on a number of recorded video sequences)

whether each signal on the two test routes is located in the search box at 80 m and 50 m from an intersection, assuming that the vision system can detect the correct indication once the signals' search boxes were correctly placed. This analysis does not distinguish between lateral and longitudinal position offsets of the signal position reported by the map (relative to a vehicle approaching an intersection) and ground truth. Both actually manifest as a lateral offset in the two-dimensional camera image. However, differences in the 50 m and 80 m analysis are due to longitudinal signal position inaccuracies. For example, a signal head with a large longitudinal position error, i.e., placed too close or too far away from the vehicle relative to the true signal head, would "wander" in and out of the search box as the vehicle approached the intersection. The original specification called for a longitudinal signal head accuracy of 3 meters and a lateral signal head accuracy of 2 meters relative to the direction of travel of a vehicle approaching a signal controlled intersection.

On the California evaluation route, only about 40% of the signal heads were located in the appropriate search box at 80 m from the intersection, and about 47% were located in the search boxes at 50 m. The Michigan evaluation route yielded similar results. At 80 m, about 47% of the signal heads were located in the search box, and 50% of the signal heads were in the appropriate search box at 50 m from an intersection. That the system still performed well, even with this large amount of wrongly placed signal heads, is due to redundancy of signal heads at an intersection. A particular signal head might actually be located in a search box reported by the map as belonging to a different signal head and, in turn, be correctly identified. Figure 2-24 shows such an example. This behavior, though, is purely by chance and would not be acceptable in a production version.

Despite the findings previously discussed, the TSA correctly identified the signal indication at many intersections—particularly complex intersections with turn lanes controlled by dedicated signals. Complex intersections are really the key areas in which the map can help reduce false detections. For simple intersections, there is no noticeable difference between the detection rates of vision only and map/vision systems. In fact, in some situations, adding the map seems to make the detection slightly worse. This is due to falsely reported signal head positions in the map.

The advantages of the map become apparent, however, when intersections that are more complex are examined. Figure 2-25 shows how the two systems fared in more complex environments. Here, the two grouped bars represent two drives that were used to assemble this graph. In all cases, the information from the map improved the detection rate and greatly reduced the failure rate of the system. Many examined intersections had left turn signals controlling dedicated left turn lanes. In almost all cases, the vision-only system would detect the left turn signal and the through signal, many times issuing a false alarm to the driver (in most situations, the through lane signals indicated green, which was the path that the vehicle took, whereas the left turn signal showed a red indication).

2.4.2.3 Signal Detection

The current implementation of the Traffic Signal Assistant was optimized to detect signals on the California and Michigan test and demonstration routes. It is written to detect the indication on 3-lens, vertically mounted signal heads, which are most common in the two test areas. The design of the route was chosen in order to challenge the application with a variety of situations. Nevertheless, the limited size of the test area did not allow testing of the system behavior under all possible conditions. The two main aspects that were not fully investigated were:

- Reduction of the effects of adverse weather and lighting conditions
- Signal configurations other than the ones found on the demonstration routes

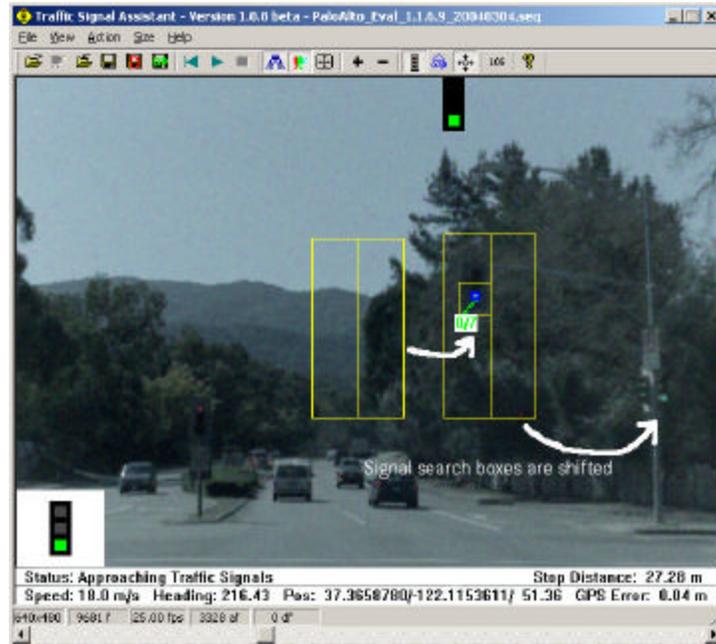


Figure 2-24: Signal heads and map-reported position disagree, although the correct signal indication is still identified

Naturally, changing weather conditions were encountered on the test drives. For example, bright sun, rain, and fog were encountered and their effect on the system performance was noticeable. In fact, sun posed the most challenges to the vision system. In particular, sun glare due to low position of the sun (mornings and evenings) had the largest impact on system performance. Sun glare would wash out the color in the images and produce aperture rings. In this case, the system might confuse a round shape in the images with a signal or detect the signal indication significantly later.

At other times, low sun originating from behind the vehicle would cause the signal heads to reflect the light in all three lenses, and even a human could barely determine the signal indication. In those situations, the vision system always failed to identify the signal indication correctly and reliably while approaching the intersection. It proved that cloudy skies posed the best conditions for the traffic signal detection. Light to moderate rain was encountered on several drives and did not influence the performance significantly. The camera view was cleared well by the windshield wipers. Heavy rain and heavy snowfall, although not encountered, are expected to have a significant impact. Heavy fog was encountered on one drive and it rendered the system unusable. The visibility was estimated to be around 100 m on that particular drive, and the signal indication was detected too late. Although night performance was not specifically evaluated, several drives were conducted after sunset during late evening in order to get an idea of system performance under adverse lighting conditions. On the test drives conducted, the system performed unexpectedly well.

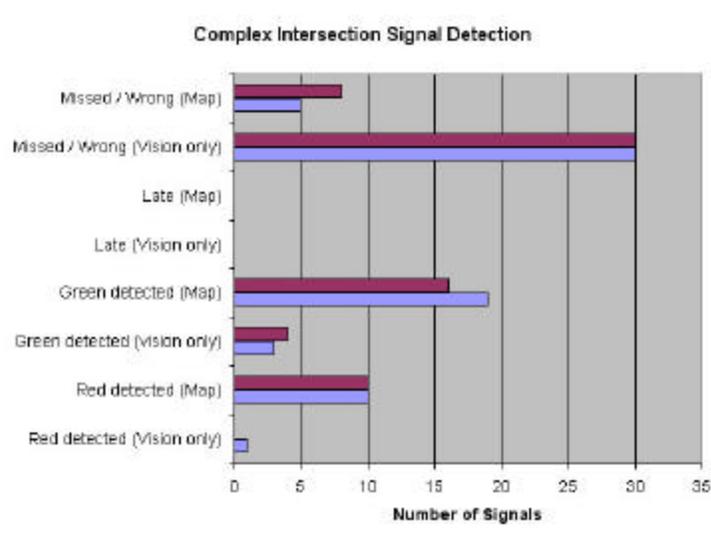


Figure 2-25: System comparison at complex intersections

As mentioned before, the system performed well on the signal configurations encountered on the demonstration and evaluation route. Even on those routes, several very challenging signal configurations were identified that would not allow the detection to function accurately. Figure 2-26 shows two signal configurations that were present on the evaluation route that posed a challenge to the system.

Configuration (1) places two signal heads very close together. In this case, both signal heads controlled the left turn lane. However, had the two signal heads controlled different lanes, the system could not have identified the indication correctly. Configuration (2) shows a very difficult scenario. Two signal heads (the upper one controlling the through lane and the lower one controlling the left turn lane) are mounted on the same pole. The system was not able to correctly identify the signal indication (the vehicle traveled in the through lane in this example). Additional signal head configuration information in the map could help to classify various detectable or unusual configuration and thereby further aid the vision system. However, in some very challenging situations the vision system would still have to be disabled.

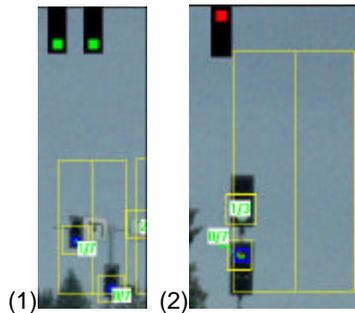


Figure 2-26: Challenging signal configurations

LED signals were also found to be difficult to detect at times. Because of the directionality of the light emitted from the LEDs, the signal indication would be detected late on signal heads pointing slightly downward (intentionally or unintentionally).

In addition, there are a variety of other signal head configurations outside the demonstration area that are currently not supported. The following images show only a small variety of signals that the current system cannot detect reliably.

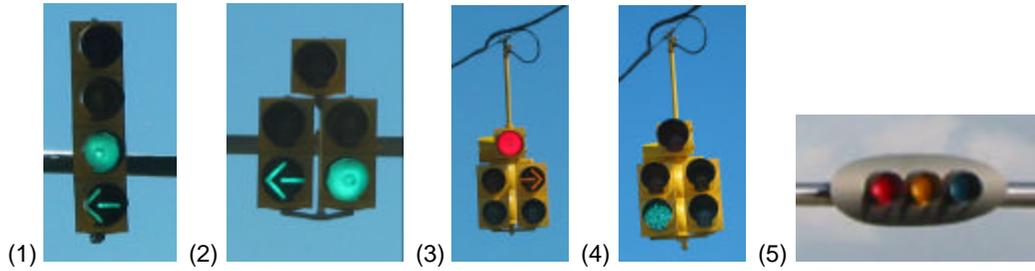


Figure 2-27: Signal heads that cannot be detected with the current system

2.4.2.4 Revised Map Requirements

Overall, the original map requirement worked very well. The stopping location accuracy was able to be relaxed slightly to 3 m (instead of the 1 m accuracy initially requested). Table 2-9 shows the new requirements. No additional maplets were needed to perform the application. Signal head height, however, would be beneficial. The height would have to be reported as height above sea level, though, and not as height above the road. Height above the road would require very accurate grade information of the road in order to project the signalsearch boxes correctly.

Table 2-9: Maplet requirements

Mid-term Maplets	Revised Maplet Requirement
Stopping Location	Relaxed to 3 m accuracy
Traffic Signal Location	3 m longitudinal and 2 m lateral accuracy; Absolute height would be beneficial

2.4.3 Vehicle Positioning Performance and Analysis

The positioning accuracy for this application is not quite as critical as long as the vehicle is matched to the correct lane. For example, the application can deal with a GPS error of up to 1.0 m, assuming a map accurate to about 1.0 m. During testing, a GPS error of more than 1.0 m would cause, at times, the map to match the vehicle to the wrong lane. Theoretically, the combined error (map and positioning) should be about one-half of the lane width, which would be about 1.70-2.00 m. Nevertheless, as long as the map system matches the vehicle to a lane that is controlled by the same signal heads, the application has a chance of still functioning correctly. If, on the other hand, the vehicle is erroneously matched to a left turn lane (which happened quite frequently at GPS errors above 1.0 m when traveling in the left-most through lane), the application would get incorrect signal information and would give the driver a false warning. Therefore, TSA was disabled any time the GPS error went above 1.0 m. On the Palo Alto evaluation route, a very low GPS error was generally experienced on segment 1 (locations 1-6 and 25-34), and a GPS error of up to 2.5 m was experienced on segment 2 (locations 8-24). Hence, the application was generally disabled for portions of the drive along segment 2.

Figure 2-28 shows intersection 11 on segment 2. Due to heavy tree cover, the GPS error rose to 0.88 m (1). After stopping at the intersection for some time with no trees covering the GPS antenna, the GPS error would drop to 0.55 m (2). After even more time passed and the GPS receiver had a chance to re-acquire the lost satellites, the GPS error would drop to a very good 0.04 m (3). The time span between image (1) and (3) is roughly 16 seconds. The time span between image (2) and (3) is approximately 14 seconds. As one can see, at each GPS error drop, the signal search boxes would “jump”, reflecting a better vehicle position. This jump would be particularly apparent if the GPS error had a large lateral component (relative to the driving direction of the vehicle). At times, though, a lower GPS error would not result in a “jump” of the search boxes at all.

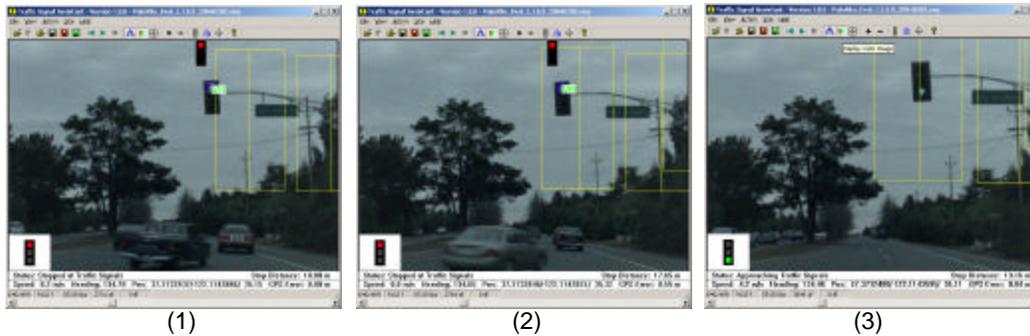


Figure 2-28: Effects of GPS error on signal search boxes

This warning portion of the system was susceptible to increasing GPS errors. In addition, assuming a GPS error below 1.0 m – the warning portion would be disabled above this error – no benefit was noticed in adjusting the warning distance based on degrading GPS performance.

2.4.4 Possible Deployment Options and Potential Safety Benefits

Given the results of this project, the mid-term deployment timeframe for the Traffic Signal Assistant originally estimated has been confirmed, under the assumption that the signal head positions can be mapped accurately enough in a large-scale database release version. The Honeywell PAPS lane-level positioning system performed satisfactorily and the accuracy encountered proved not to be a limiting factor for the deployment of this kind of system.

For complex intersections (dedicated turn signals are present), the integration of map and positioning has a decidedly beneficial effect. The integrated system had a detection error of about 20%, whereas the vision-only system had a detection error of 90%. This is mainly due to dedicated turn signals misleading the vision-only system. The errors encountered are due to the dynamic nature of traffic scenes, e.g. changing weather conditions, changing traffic patterns and density. For complex intersections, the only way of increasing the effectiveness of the system is better map quality (mapping of the signal heads). Two alternatives that could help increase accuracy of the signal head positions are:

- Stereoscopic video recording and placing signal heads using photogrammetry
- Manual placement of signal heads during edit process

Stereoscopic photogrammetry would be less labor intensive and is expected to yield better results. Some additional benefit can also come from including signal head altitude to further restrict the vertical extent of the search area. All of those suggestions would result in an increase in cost and effort of the data collection and map database creation.

For simple intersections (no dedicated turn signals are present) it was found that adding the Map/GPS System makes the overall system perform somewhat worse than the vision-only recognition. This is due to falsely mapped signal head positions. With the integrated system the percentage of missed, wrongly detected signals or signals detected too late, was 36%, whereas the vision-only system missed only 27% of the intersections. Using the integrated system, virtually all the missed signal heads in simple intersections were detected erroneously because of inaccurately mapped signal head positions. The lateral error was more than 2 m in those cases. For simple intersections, performing a full screen search, which does not need the exact position of the signal heads, can actually reduce the error rate. This still means an error increase and potential safety benefit decrease over the ideal situation of roughly 20-30%. However, simple intersections could be supported by this application even without a lane-level map. The map would only need to identify upcoming signal-controlled intersections. Thereby, the map creation and editing effort can be greatly reduced for those scenarios.

However, since weather and other external influences (e.g. artificial lighting, other vehicles on the road) play an important role in the detection accuracy of the vision system, the overall effectiveness cannot be exactly estimated. Solar glare is especially difficult to compensate for and will cause errors on roads in easterly and westerly directions. Assuming good environmental conditions and precise maps, the overall detection error should be small but an accurate number cannot be given.

2.5 Lane Following Assistant

2.5.1 Application Performance and Results

DaimlerChrysler developed a Lane Following Assistant (LFA) operating in warning mode, also commonly referred to as Lane Departure Warning (LDW). The goal of the application in this mode is to warn a driver when the vehicle is leaving the lane. The application is a combination of a vision lane tracker and a Map/GPS system. The main goal for adding map and positioning information to aid the camera-based system is to enhance the vision system portion by reducing system outages and false or missed warnings. The map portion of the application is based on a lane-level map and the Honeywell Prototype Automotive Positioning Sensor (PAPS). Generally the two systems (vision and Map/GPS) can operate simultaneously and will deliver very similar output variables, most importantly the offset from lane center, lane width, lane curvature and geometry ahead. Hence, there should be a high potential for sensor fusion, which allows an overall system to choose the best available sensor (vision or Map/GPS) to determine the vehicle's position in the lane and predicted travel path. However, due to insufficient map accuracy and vehicle positioning errors discussed later, sensor fusion was not possible. Nevertheless, the information from the map and the GPS can still be used to aid the vision system. For example, one of the most critical parameters the vision system estimates is road curvature and curvature change of the road ahead. A very accurate map can greatly assist the vision system by providing a road geometry preview. Other potential aids to the camera-based system are the lane markings type and lane width. Unfortunately, the delivered map database and overall GPS performance did not allow the use of many map attributes as inputs to the vision lane tracker. Only the lane markings type, lane width (both of which had a marginal impact on the vision system performance), and intersection location were utilized during our testing.

The yaw rate, delivered by the Honeywell PAPS unit, was used as a vision system input to estimate the vehicle trajectory. The overall vehicle speed was also evaluated and the system was only active above 20 mph. Turn signal information from the vehicle was used to infer driver intention and deactivate the system when the driver seemed to intentionally depart from the lane.

Due to map problems in the Palo Alto test area, the overall impression of the Lane Following Assistant in California was mediocre at best. In Michigan, however, an improved map helped to give a slightly better impression. Refer to Figure 2-29 for the route locations of the California and Michigan demonstrations. Since data fusion was not possible, the two systems operated independently, except for a small amount of route preview information that the vision-based system receives from the map. The vision-based lane tracker performs very well. It detects the lane edges very reliably and is able to infer the vehicle position within the lane most of the time. This is true even for lanes that have Botz dot lane markings on both sides (California test area). The Map/GPS system, on the other hand, very reliably places the vehicle in the correct lane; however, it does a poor job determining the vehicle's position within that lane, rendering it virtually useless as a lane departure warning. The reasons for this outcome fall into two basic categories:

- Poor map accuracy
- Unreliable high precision GPS at times (this includes differential correction coverage)

In many cases the errors in both the map and GPS are not completely separable and may actually compound or eliminate each other.



Figure 2-29: California (left) and Michigan (right) demonstration and evaluation route

While both systems ran simultaneously during the demonstrations, only one system was enabled to deliver a warning sound at any given time. In addition, the map lane centerline and lane width were projected onto the vision system camera image for easy real-time comparison of the two systems. The demonstrator vehicle was then driven twice on a particular stretch of road, the first time with the vision system warning sound enabled and the second time with the Map/GPS system delivering the warning sound. The Map/GPS system delivered noticeably more false alarms where lane geometry accuracy was low.

2.5.2 Mapplet Analysis

The Lane Following Assistant originally intended to incorporate more mapplets than it actually did. Two main inputs to the vision-based system are lane curvature (derived from lane geometry) and lane marking type. The vision lane tracker can use the lane markings type to adapt its search window size. The search window size can be enlarged to detect solid lane markings, set to a medium size for dashed lane stripes, and reduced to a very small size if Botz dots were present. Overall, however, the lane markings type had a marginal impact on the vision system performance.

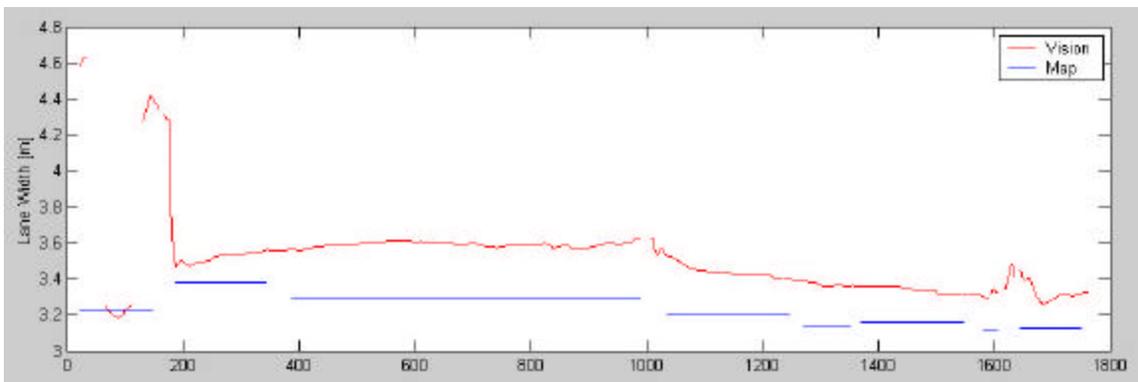


Figure 2-30: Typical lane width differences (Page Mill Rd.)

Typical lane width differences (Page Mill Rd.) as a function of distance traveled (meters)

Further discussion in this section will concentrate only on the evaluation routes in California and Michigan, since those roads were analyzed in greater detail than the remainder of the map database. However, the mapplet accuracies experienced on the evaluation route are generally representative for the entire database coverage areas. The sections examined represent typical scenarios in which the Lane Following Assistant would be expected to work. Overall, about 6.5 km of the evaluation route was inspected closely.

The Lane Following Assistant uses the lane width mapplet to detect grossly inaccurate readings from the vision system and this mapplet is used by the Map/GPS system to calculate the moment the vehicle leaves the lane. In the first scenario, the lane width reported from the map is compared to the value the vision lane tracker infers. Here the lane width acts merely as a supporting parameter. If the difference in lane width reported by the two systems is more than 0.5 m, the vision system is reinitialized, assuming that it erroneously picked up a wrong lane edge. This increases the stability in transition zones, where lane markings diverge because of a lane forming or ending. Theoretically, a very good lane width agreement, i.e., less than about 0.05 m difference between the vision and Map/GPS systems, can be used as a fusion parameter. Figure 2-30, shows the lane width difference between the two systems on an 1800 m long road segment. This is a very common scenario with the maps used. The difference of up to 0.30 m is still acceptable for the purposes of supporting the vision system.

As mentioned earlier, the lane width is not only used to detect vision system error behavior, it is also critical in determining the lateral vehicle position within the lane by the Map/GPS system. In this application, the detected offset from the lane centerline, the lane width, and the vehicle width are used to calculate the distance to the lane edge remaining on either side of the vehicle. Since a warning is issued if the vehicle crosses the lane boundary, i.e., the space between the vehicle and the lane marking is 0.0 m, an erroneous lane width will influence the warning behavior of the Map/GPS system. Given that this is a very crude method of a lane departure warning, it is still sufficient for the purposes of this application. A time-to-line-crossing approach would show a somewhat better warning behavior and would permit elimination of false warnings due to cutting a corner.

The original map requirement for the Lane Following Assistant was such that the combined error of lane width and centerline accuracy was not to exceed 0.3 m. For example, if the lane width differs by 30 cm from the true lane width, the lane centerline has to be perfectly accurate; or if the lane width is perfectly accurate, the lane center can be up to 30 cm from ground truth; or any other combination of the two.

Figure 2-31 shows a comparison of the vision and Map/GPS systems. The plots represent a 4.5 km segment of I-280 in the Palo Alto evaluation area, about one fifth of the entire evaluation route. The x-axis always refers to distance driven in meters.

Figure 2-31 shows the position of the vehicle within the lane and the errors of the map. The first two graphs depict the position of the vehicle within the lane, derived from the Map/GPS system and the vision system, respectively. The black lines indicate the lane boundaries (derived from lane width) and the curved lines indicate the left and right wheel position within the lane. It is helpful to imagine the vehicle driving from left to right and the lines representing the tire marks it leaves on the road. The green, yellow, and red highlighted areas in the first graph will be discussed later. Gaps in the map data denote that the vehicle was not map-matched, in an intersection, in a transition zone, or that the GPS error rose above 0.2 m.

Particular care was taken to ensure a low GPS error during the collection of data discussed here—mainly to allow for a good evaluation of map quality independent of GPS error behavior. Gaps in the vision system data indicate a bad vision system status. Areas of good GPS and vision system data will be focused on in later discussions.

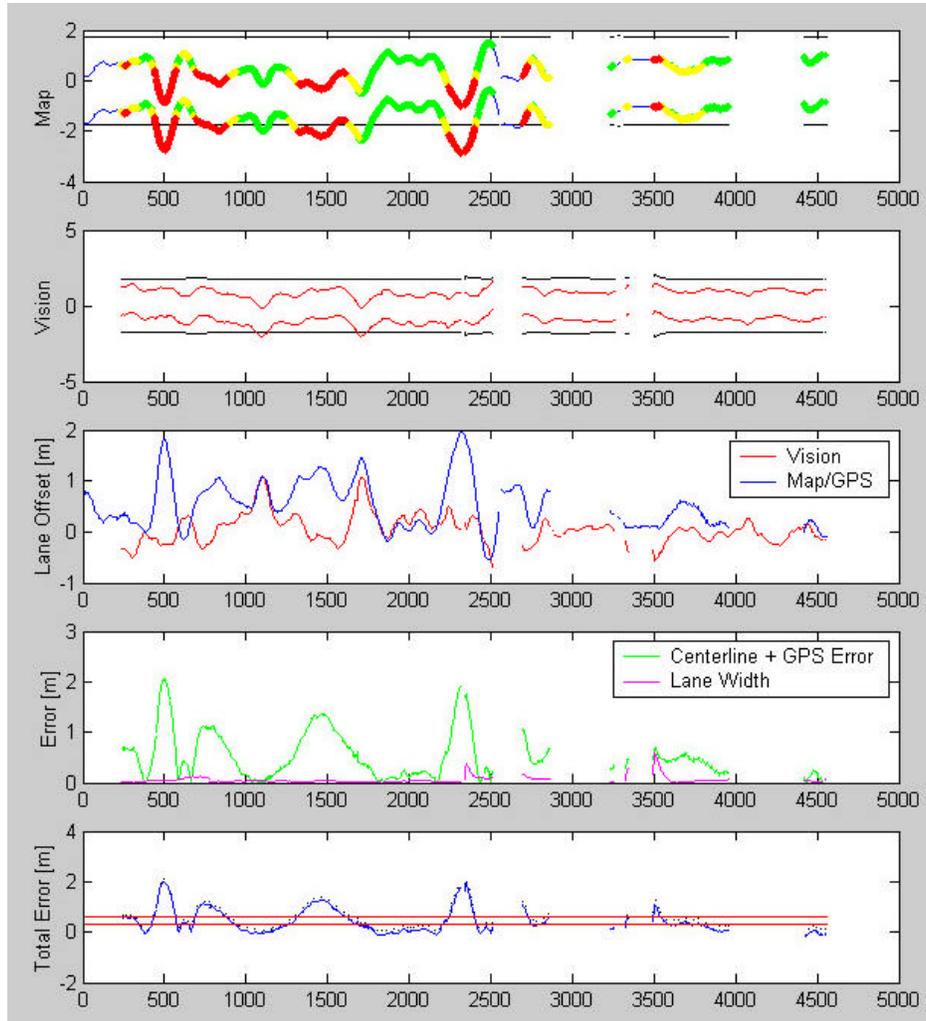


Figure 2-31: Differences between vision and Map/GPS systems

Differences between vision and Map/GPS systems as a function of distance traveled (meters)

In order to evaluate the map performance, the vision system output was used as a reference and ground truth. The vision system status flag would indicate good data from this system. Using the Honeywell PAPS GPS position, heading, and vision lane offset along the path, the true centerline points of the road can be easily calculated. This approach was verified by collecting data for multiple runs for each piece of road that was examined closer. Given low GPS errors, the resulting lane centerlines usually fall within 5 to 10 cm of each other, making them a very good basis for comparison. Since the map system also delivers map centerline points, the difference of the centerline position reported by the map to the ground truth (calculated) can be evaluated.

The third graph in Figure 2-31 shows the two lane offsets (a right offset is positive). The fourth graph shows the absolute value of the difference in lane width between the two systems, and the absolute difference of the map centerline from the calculated centerline (green line). The latter also includes a portion of the GPS error. Here the two errors (map and GPS) might compound each other or cancel each other out. They are virtually inseparable. The fifth graph depicts the total difference of the Map/GPS system compared to the vision system. Here the absolute lane width difference and the absolute offset of the map centerline from the vision-calculated

centerline are added (black dashed line). Since the GPS error is known at any given time, the error can be subtracted from the total error and an estimated map error can be extracted (solid blue line). This graph also shows two horizontal lines, one at 0.3 m error and one at 0.6 m total error. The line at 0.3 m represents the original map specification, i.e., the combined error of lane centerline and lane width was not to exceed 0.3 m. The line at 0.6 m was chosen as a relaxed requirement of a 0.3 m error for each value individually (a 0.3 m error tolerance in lane width and a 0.3 m error tolerance in centerline accuracy).

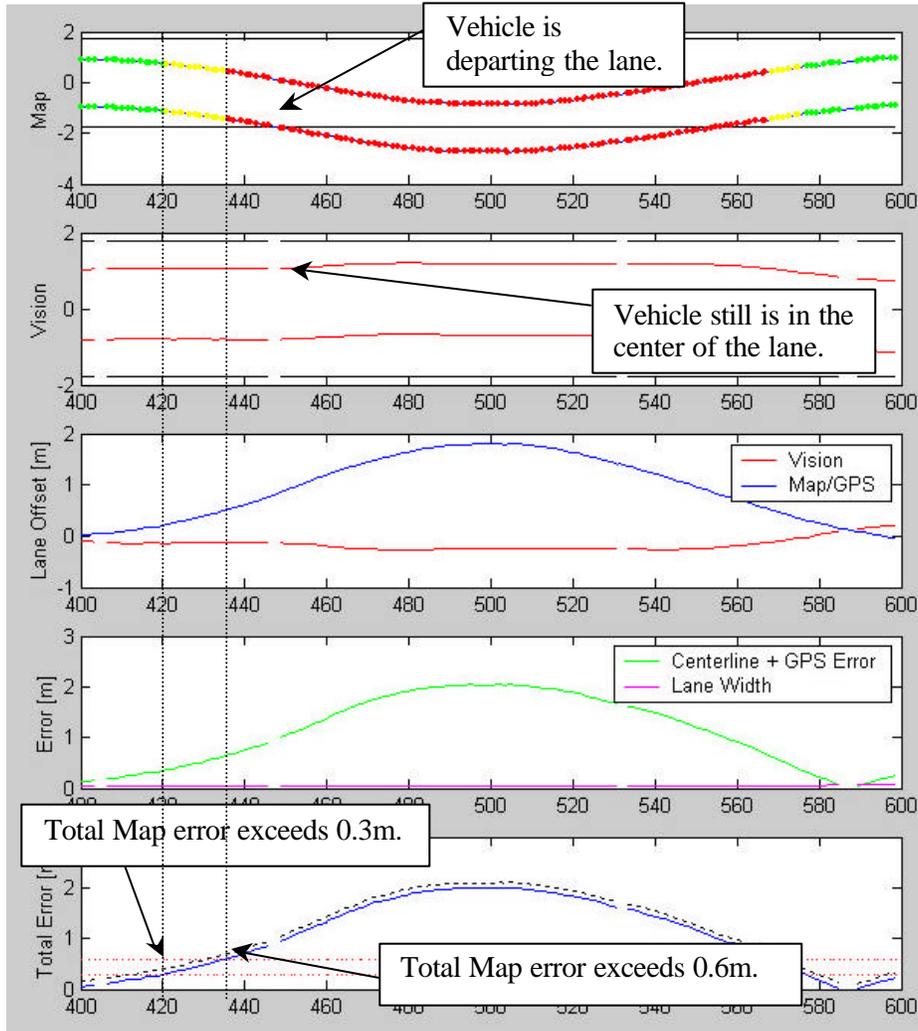


Figure 2-32: Section between 400 m and 600 m exceeds allowed error tolerance

Section between 400 m and 600 m exceeds allowed error tolerance. X axes are in meters traveled.

Figure 2-32 shows the section between 400 m and 600 m in more detail. Here, the Map/GPS system clearly shows the vehicle departing the lane at about 450 m along the driven path. This, however, is a false alarm, since the vision system still shows the vehicle in the center of the lane. This is a typical example of an erroneous map centerline. In this particular case, the lane centerline deviates from the ground truth by about 2.0 m; the lane width in this particular case is accurate to about 0.06 m. The highlighted areas in the top graph (map vehicle position) denote the map error larger than the original specification of 0.3 m (yellow) and a map error larger than the

relaxed specifications of 0.6 m (red), as discussed earlier. A map error of below 0.3 m is shown in green. Non-highlighted sections show areas where not enough data existed to make an assessment, e.g., the vision system did not deliver good data. The GPS error in this section was about 0.1 m. Referring back to Figure 2-31, one can clearly see that the map did exceed the allowed error tolerance on a large part of this particular stretch of the California evaluation route.

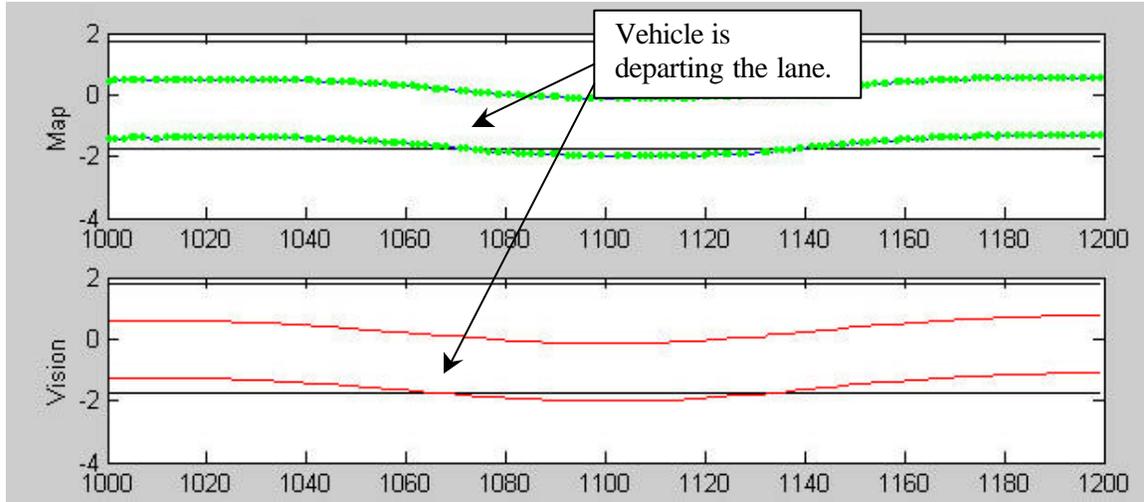


Figure 2-33: Genuine warning; vision lane tracker and Map/GPS system examine the vehicle leaving the lane

Genuine warning; vision lane tracker and Map/GPS system examine the vehicle leaving the lane. X axes are distance traveled in meters.

Some other examples of warnings will now be examined. Figure 2-33 shows an example where both systems verify the vehicle leaving the lane. The map system identifies the lane edge crossing at 1069 m along the path, whereas the vision system determines the edge crossing at 1070 m along the path. At freeway speeds, this difference is not noticeable to the driver. The total map error is between 0.05 and 0.1 m at the point where the vehicle leaves the lane. It is made up of 0.04 m of lane width error, and the remainder represents lane centerline inaccuracies. The map behaves very well on this 200 m road segment.

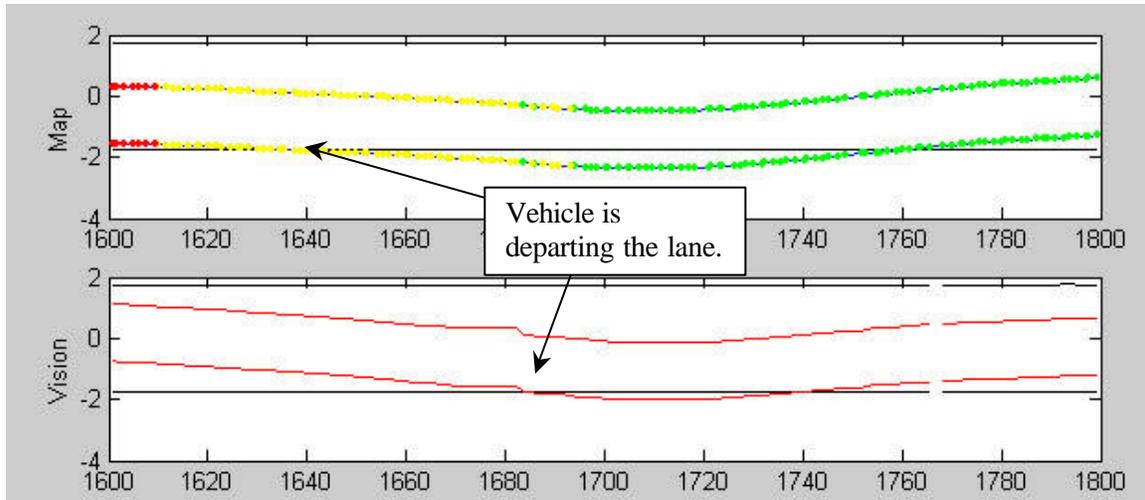


Figure 2-34: Vehicle is leaving the lane and Map/GPS system reports crossing of lane boundaries early

Vehicle is leaving the lane and Map/GPS system reports crossing of lane boundaries early.
X axes are distance traveled in meters.

Figure 2-34 depicts a warning situation that is also recognized by both systems. However, map inaccuracies lead to a premature warning by the Map/GPS system. In this particular case, the map exceeded the 0.3 m of error tolerance during most of the departure maneuver and even exceeded the relaxed 0.6 m error tolerance just before the lane departure. The map warns the driver prematurely by just over 50 m, when the vehicle was still about 0.7 m from the right lane edge (according to the vision system). The maximum departure from the lane is 0.62 m (map) and 0.25 m (vision).

Figure 2-35 shows yet again a warning by the Map/GPS system. This time the map is within the relaxed error tolerance of 0.6 m when the warning occurs. The vision system shows the vehicle moving towards the right lane marking, but not leaving the lane. The vehicle is, in fact, still 0.48 m from the lane edge. This particular example shows that even the relaxed error allowance of 0.6 m is not enough to minimize false warnings by the Map/GPS system. The original requirement of 0.3 m of combined lane width and lane centerline error proved to be a good choice.

On the Michigan demonstration and evaluation route, the map behavior was examined with an initially created map and later with a revised map that fixed some of the geometry issues that were present in the California map database, as discussed above. Not all map errors were corrected; however, poor quality of the initially collected data was determined as the root cause for most of the inadequate lane geometry. At first, the map geometry on the Michigan evaluation route behaved similar to the one found in California. After addressing the discovered map inaccuracies, a large improvement in map quality was achieved. Figure 2-36 shows the average map error found on the California evaluation route. Only 29.2% of the map sections examined fulfills the requirement for this application (less than 0.3 m of map error). For 27.3% of the map data, the error exceeded an unacceptable 0.6 m. The largest portion of the evaluated map (43.5%) falls into the relaxed error requirements (between 0.3 and 0.6 m of total map error), which was found to be unsuitable for this application (see above).

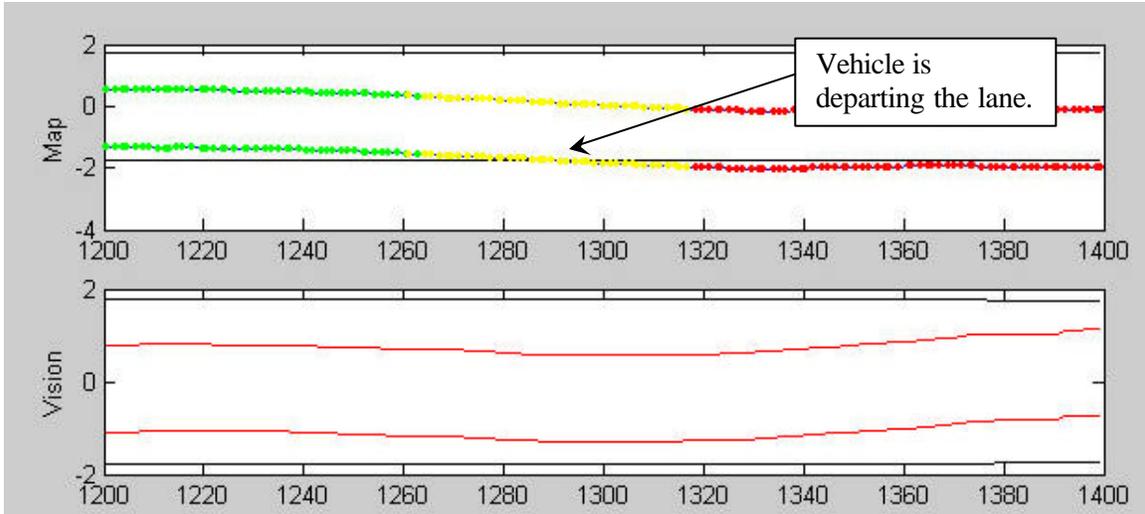


Figure 2-35: Map/GPS system issues a warning; vision system shows vehicle well within the lane

Map/GPS system issues a warning; vision system shows vehicle well within the lane.
 X axes are distance traveled in meters.

The initially created map for the Michigan test area showed a similar error distribution. A relatively small portion of the map (40.1%) fulfills the application requirement of less than 0.3 m map error.

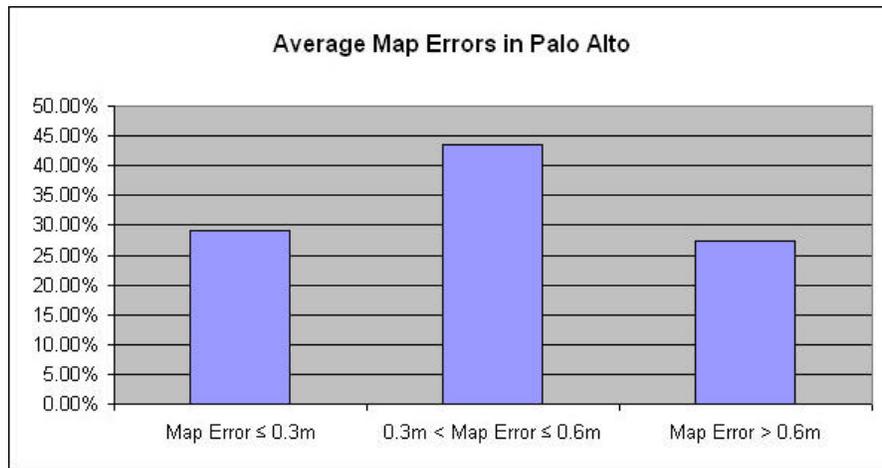


Figure 2-36: Average map error examined on Palo Alto evaluation route

After recollecting data on the examined road segments in Michigan and recreating the lane centerlines, the error was greatly reduced. In a later version of the map database, the total amount of acceptable map segments (error below 0.3 m) rose to an average of 63.5%. However, two road segments on the Michigan evaluation and demonstration route should be considered separately. Figure 2-37 shows the map accuracy improvements on some segments on M-5 north and M-5 south that were examined more closely. The improvement on the southbound road segment was significant. On this section, 80.6% of the map was found adequate for the Lane Following Assistant application (up from 53.1% initially).

During the application demonstration in March 2004, the southbound portion of the drive delivered mostly acceptable lane departure warnings based on the Map/GPS system only. The northbound section, however, still delivered several false alarms and proved unreliable for a warning based on the Map/GPS system, further establishing the requirement of less than 0.3 m map error (centerline and lane width).

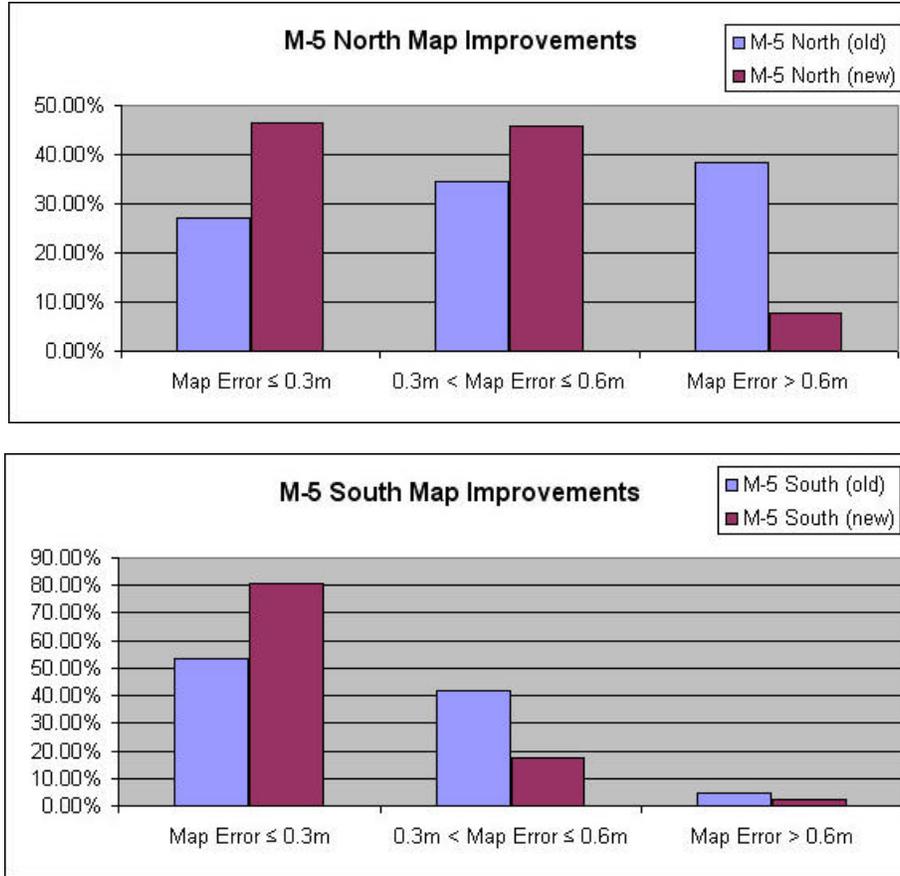


Figure 2-37: M-5 north and south improvements

Curvature was an additional parameter that was evaluated. A good lane/road curvature can greatly improve the vision system performance and resolve ambiguities. Figure 2-38 depicts the curvature on the same 4.5 km segment of I-280 that was discussed above. The plot combines the data of six drives along the route. The upper graph shows the lane curvature that the vision system determined (red) and the lane curvature calculated from the lane centerline spline (blue). The lower graph shows instantaneous curvature calculated from the vehicle yaw rate and speed. On this particular road segment, two areas of significant curvature deviation were identified.

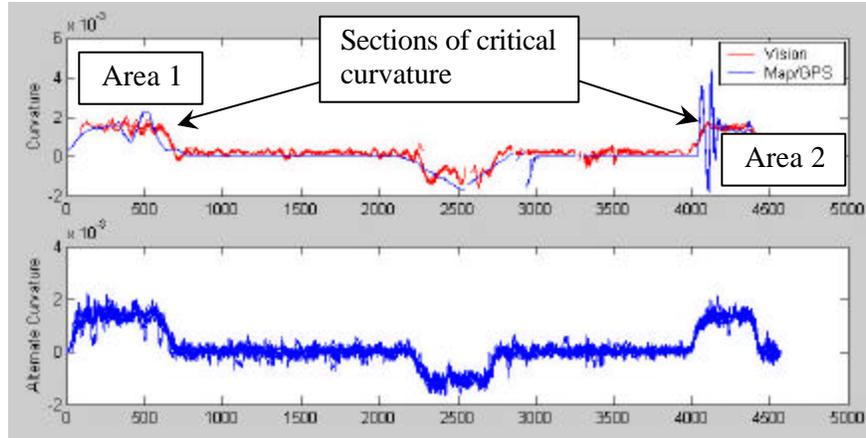


Figure 2-38: Curvature on 4.5 km segment of I-280 (6 traces)

In area 2 the map shows a curve radius of about 284 m to the right, followed by a curve of 566 m to the left, followed by a curve of 227 m to the right, and again followed by a curve of 532 m to the right. The vision system and alternate curvature, on the other hand, detected a curve with a relatively constant radius of 650 to 700 m to the right.

The curvature fluctuation was noticed in many curves and curve transitions in the Palo Alto test area, rendering it useless as a reliable input to the vision system. A possible solution would be to filter the curvature values retrieved from the map; however, this was not further investigated during this project.

The following table summarizes the mapplets that the Lane Following Assistant currently uses and reflects updates of any newly discovered requirements.

Table 2-10: Lane Following Assistant maplet requirements

Mid-term Maplets	Revised Maplet Requirement
Lane Geometry	Combined absolute lane centerline + lane width accuracy of 0.3 m
Lane Width	See Lane Geometry
Lane Curvature	Not useful as delivered; 10% accuracy is reasonable
Intersection Location	10 m accuracy
Adjacency	Additional maplet that combines several others
Transition Zone	Used as currently delivered to reduce false alarms; 10 m accuracy reasonable
Shoulder Type	Not used; useful to adjust warning threshold. 3 categories needed: <ul style="list-style-type: none"> ▪ Non-drivable (i.e., curb, unpaved shoulder) ▪ Drivable (paved) and ≤ 0.5 m wide ▪ Drivable (paved) and > 0.5 m wide
Shoulder Width	See Shoulder Type
Adjacent Lanes	Number of lanes to the left and right of the vehicle
Lane Markings Type	Not required
Road Surface Type	Not required
Intersection Geometry	Not required

During the EDMap project individual lane splines were used to represent the lane centerlines in a road segment. This lane representation proved sufficient for most demonstrated applications, however, the complexity of the spline fitting process seems to have introduced some errors that the LFA-W application struggled with. A possible alternative would be to store a road centerline spline and offsets for each of the lanes on the road. Conversely, a simple shape point or clothoid representation could be used. None of these options were evaluated during this project and it would be purely speculative to assume any improvement.

2.5.3 Vehicle Positioning Performance and Analysis

In this section, the Honeywell PAPS performance relating to the Lane Following Assistant (warning mode) is discussed. At the beginning of the project, the GPS positioning accuracy requirement for this application was specified to be 0.3 m. Combined with a specified map accuracy of also 0.3 m, the total accuracy required to perform this application was originally 0.6 m. During the experiments conducted, however, it was found that the Honeywell PAPS unit positioning error would generally be below 0.2 m when the positioning system was operating under good conditions. The GPS error would then climb relatively quickly and exceed 0.5 m when obstacles blocked some or all satellites. Therefore, the application was limited to only accept GPS positions if the error was below 0.2 m. This would leave the complete system error (map + GPS error) at 0.5 m, slightly lower than originally specified.

Since the Lane Following Assistant is very sensitive to GPS errors, the overall impression was that the Honeywell positioning device did not perform well for this application. Figure 2-39 shows the GPS error on a typical drive on the Palo Alto evaluation and demonstration route. On this particular drive, which can be viewed as an example of normal driving, the GPS error was below 0.2 m for about 75 % of the time of the drive. The driven route follows an arterial road (with very little tree coverage) and a freeway, which includes an exit ramp where the vehicle passes a series of overpasses in a short period of time. This causes the GPS error to remain unacceptably high for an extended period of time and rendered the Map/GPS portion of the Lane Following Assistant inactive. The highlighted section (red circle) on the plot corresponds to that scenario. The GPS unit lost high precision positioning for about 2.5 km before recovering to a good position.

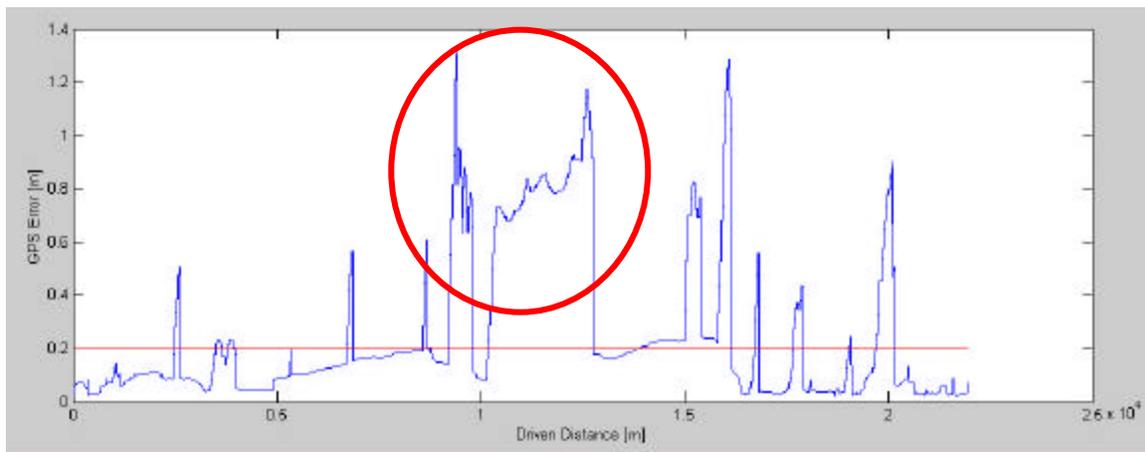


Figure 2-39: Changing GPS error on a typical drive on the Palo Alto evaluation route (total length: 21.9 km)

A more detailed and general discussion of vehicle positioning can be found in Chapter 4, *Positioning Systems*, of this report.

2.5.4 Possible Deployment Options and Potential Safety Benefits

The deployment of a Lane Following Assistant (Warning) (LFA-W) application can actually be divided into several stages:

- Vision-only lane departure warning systems
- Gradual deployment of map-aided systems:
 - Simple Map/GPS aid (WHATROAD application)
 - Higher Accuracy Map/GPS aid (WHICHLANE application)
 - Vision and Map/GPS Fusion (WHEREINLANE application)

Vision-only based Lane Departure Warning (LDW) systems have been in the research phase for a long time and very stable versions of the application are now starting to enter the marketplace. Vision-only systems have already been available in the commercial truck market⁵ for some time and over the next few years, i.e. the EDMap near-term horizon, these systems will also start to be deployed in passenger vehicles in the U.S. and other parts of the world⁶. These systems mainly rely on the lane marking detection and yaw rate information from the vehicle.

Although, these systems operate without the aid of a map database, even limited map information can still be beneficial. For this purpose, although not investigated further in this project, a road-level map with accurate curvature information can be used to assist a vision system and detect certain fault scenarios (WHATROAD application).

However, a high accuracy lane-level map and positioning system, as investigated during this project, has proven to be more complex than originally thought. The Map/GPS system is not reliable in itself to provide LDW functionality within near- and mid-term timeframes. Hence, the deployment of a Lane Following Assistant (Warning) application based on sub-meter accuracy lane-level map and decimeter level positioning will have to be moved further into the long-term. However, a gradual deployment of various map-aided systems can provide a reasonable alternative. Starting with the near-term deployment of vision-only systems, map information can slowly be added as more precise maps become available to further increase the effectiveness of current vision-based LDW systems.

Thus, the primary sensor for the LFA-W application is (and will be) the camera system and the functioning of this sensor is relatively independent of road class. These vision-only systems mostly suffer from insufficient lane marking quality and lane marking occlusions due to snow and rain (unpredictable reflections of wet road surface). Therefore, those systems generally only function well on roads with higher speed limits (higher than 40 – 45 mph, for example), which usually have better lane markings such as freeways and major arterial roads. The addition of a Map/GPS System has the potential to more reliably bridge vision system outages and adverse road conditions such as poor lane markings and lane transition zones. The main problem with Map/GPS System, however, is that the combined error (map error and positioning system error) is usually larger than 30 cm. As analyzed in section 2.5.3 positioning system errors can increase rapidly under unfavorable roadway environments, particularly satellite outage conditions. In addition, very high positioning precision is currently only achievable with Carrier-phase differential corrections, which are also prone to outages (depending on transmission method) and has higher requirements for the number of satellites that need to be available. Thus, even if the map was perfect, the performance of the Lane Following Assistant (Warning) would still be

⁵ Aftermarket LDW system from Iteris available for commercial trucks

⁶ Infiniti plans to release a U.S. product in Fall 2004

dependent on satellite visibility and DGPS outage conditions. The deployment of such a system would also depend on a large-scale availability of such differential correction data.

With very reliable curvature information and precise yaw rate sensors, an aided vision system could bridge outages of several seconds until lane markings can be detected again. This would extend the reliability and the usability of the system to other classes of roads with lower speed limits. The curvature information also helps the vision system predict the shape of the road ahead and thereby helps the vision system detect the lane markings more reliably. It can be expected that a precise curvature mapplet will be available sooner than precise absolute lane geometry and therefore this mapplet will potentially enhance the system functionality in the near-term to mid-term time frame (WHICHLANE application). If, in the long-term, maps with precise geometry become available, the system functionality and reliability can be extended to the entire road network for which this information is available (WHICHLANE and WHEREINLANE application).

According to the NHTSA 2002 Traffic Safety Facts annual report, roughly 70% of all fatal single vehicle road departure crashes happen on roads with speed limits of 40 mph and greater. Virtually all of the lane departure crashes caused by lane drift happen on those roads also. Therefore, it is concluded that by being confined to this type of road, the potential safety benefits (as identified in Task 1 of the project, see Appendix Task 1 for details) will be reduced by about 30 %. There is an additional reduction in benefit by being confined to vision lane tracking alone. Especially on roadways with Botz dots or poor lane markings, the effectiveness of the LDW is reduced. Those problem spots are statistically not normally distributed but there are local concentrations of poorly marked roads differing from state to state. Lane marking maintenance has a high impact on the functioning of the LDW system.

Assuming that the functioning of the vision based LDW and the Map/GPS system based LDW is independent it follows that the availability and error behavior for each of the two systems are also statistically independent. The test drives showed that the vision system has error rates of about 20% of the 40 mph and higher speed limit roads. Assuming highly accurate and reliable maps, we can estimate error rates for the Map/GPS system as 30% (mainly due to positioning errors). The error of the combined system is estimated to be 6% of the time, which means that the Map/GPS system would add about 10 to 15% to the reliability and effectiveness of the vision based LDW on the above-mentioned roads.

3 Map Database

3.1 Introduction

The maplet requirements for EDMap applications were outlined in Task 2 of this project. Special hardware and software subsystems were built during Task 4 to enable collection, processing, and delivery of these maplets. Based on the availability of hardware subsystems and the ability to integrate them into a data collection and creation environment, a number of alternatives were tested. Components were discontinued from further development if it was not feasible to build database using these devices within the EDMap project period.

Section 3.2 discusses the overview of the hardware architecture and the processes employed to create the near-term and mid-term databases. This section addresses the approach used in creating some of the primary maplets, namely, road geometry, lane geometry, curvature, point attributes, lane width and traffic signal.

Section 3.3 discusses the factors to be considered in deploying and maintaining the map database with these maplets. Some of the primary limiting factors are discussed in this section.

The effort to produce the near- and mid-term databases was then measured relative to the effort to produce today's commercially available navigation-purposed databases. This was done to gain an initial perspective of the relative costs to build databases that support the identified safety applications. These details are discussed in Section 3.4. The foregoing effort analyses were based on an initial analysis of creating near- and mid-term databases to support all near- and mid-term applications.

An independent team evaluated EDMap databases that were delivered to the OEMs for application testing. The approach used in assessing the database and the results from this analysis are discussed in section 3.5. The details of the quality report are attached in Appendix E, *Quality Assessment Report*.

3.2 EDMap Database Creation

Mobile mapping was one of the primary methods of data collection for EDMap databases. Limitations in other methods of collecting all the attributes reliably made it necessary to drive the roads. Some of the attributes that warrant driving are location and value of speed limits, stop signs and yield signs, traffic signals, travel restrictions, lane markings type, and shoulder type. Hence, mobile mapping was the primary technique employed to understand the feasibility and scalability of collecting and building EDMap databases.

Remote sensing was also considered as a potential alternative to collect geometry and attributes for the EDMap project. The initial studies on the diverse range of remote sensing sources revealed that remote sensing cannot be the primary source, but can be an effective augmented source for EDMap database creation. The studies on remote sensing are summarized in Appendix C, Section C.3, *Comparison of Remote Sensing Technologies*.

Probe data collection was another technique assessed to create the EDMap database. The initial research using a variety of probe devices suggested that probe data could be a potential value-add for deriving geometry as well as a number of attributes. However, further research is required for deriving this information consistently and reliably. The studies also indicated that results from probe data could be used as an additional source for map database change detection. The studies on probe data are summarized in Appendix C, Section C.2, *Probe Data*.

This section discusses the tools and techniques used for creating EDMap databases using mobile mapping techniques.

3.2.1 Definition of Terms

ADASRP	Advanced Driver Assistance System Research Platform. Data access layer software used to extract EDMap database and deliver the information of interest to the applications through CAN bus.
DMI	Distance Measurement Indicator
GAMS	GPS Azimuth Measurement System (Applanix System)
GPS	Global Positioning Systems
DGPS	Differential GPS
GDF	Geographic Data File
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
Lane-mile	Number of lanes x Road-miles
Mobile Plotting	Process used to record attributes during driving. Each mobile plot event has a latitude/longitude and the type of attribute recorded at this location.
PPS	Pulse Per Second (an output from GPS receivers that indicates the rollover of a whole second on the GPS clock)
RT	Real-time
RTK	Real Time Kinematic
SDAL	Shared Data Access Library

USGS DOQQ	United States Geological Survey, Digital Ortho Quarter Quad
WAAS	Wide Area Augmentation System
ZELink	Zebra-EDMap Link. A notation used to represent a section of road between intersections.

3.2.2 Near-term Database

3.2.2.1 Geometry

Collection

Near-term data was collected using two types of positioning systems. The first one was a Satloc DGPS receiver, which uses WAAS corrections and results in a position accuracy of 1 to 3 m. The second configuration was a combination of a Satloc DGPS receiver and a low-cost 2D-IMU. The INS solution resulted in a real-time, fused solution of IMU and the DGPS. Both systems were used with in-house data collection software. The GPS data was collected at 1 Hz and the INS data was collected at 5 Hz. Figure 3-1 shows the system components used for collecting near-term geometry and attributes.

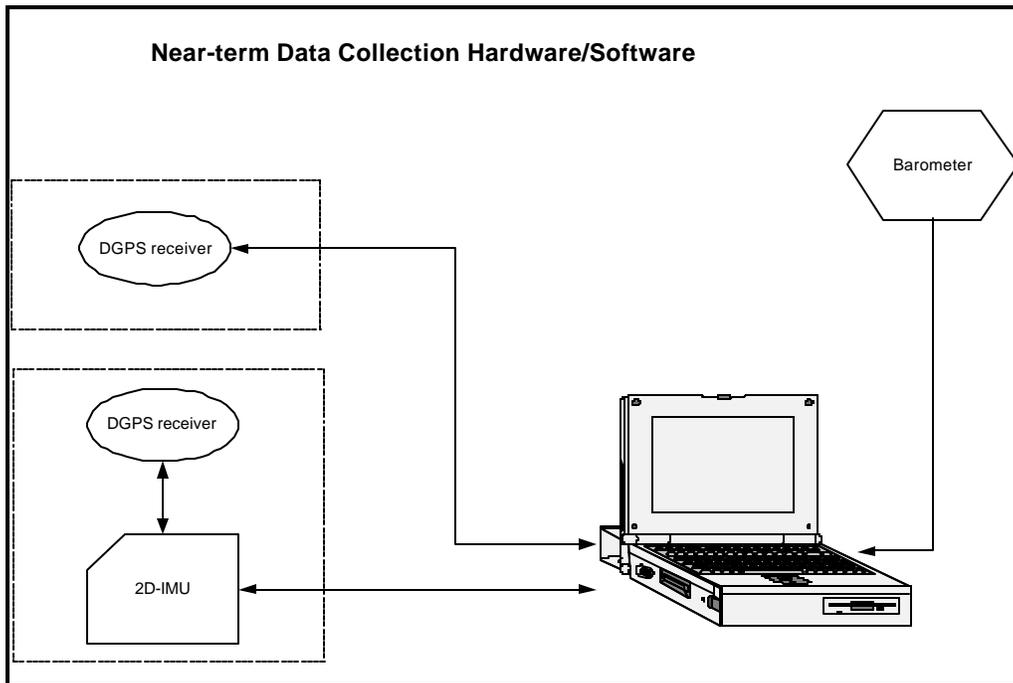


Figure 3-1: Near-term data collection system configuration

The field staff drove along the road in accordance with NAVTEQ’s well-defined data collection guidelines. A custom approach, called mobile plotting, was used to record the lane configuration and the lane in which the vehicle was positioned. This enabled determination of the road centerline relative to the vehicle path.

Processing

EDMap geometry is represented in the form of splines. Existing road geometry in the NAVTEQ database was transferred along with its attributes to an EDMap link. To meet EDMap accuracy requirements, the EDMap link was moved, as needed, to correspond to the road centerline as indicated by the GPS/INS position and lane configuration/position information from the mobile plotter. The details of database creation process is explained in Appendix C, Section C.4, Data Edit Tool.

The editors also used the remote sensing imagery to ensure that the road geometry, as derived, was in line with remote sensing imagery. Figure 3-2 shows the process used for creation of the EDMap near-term database.

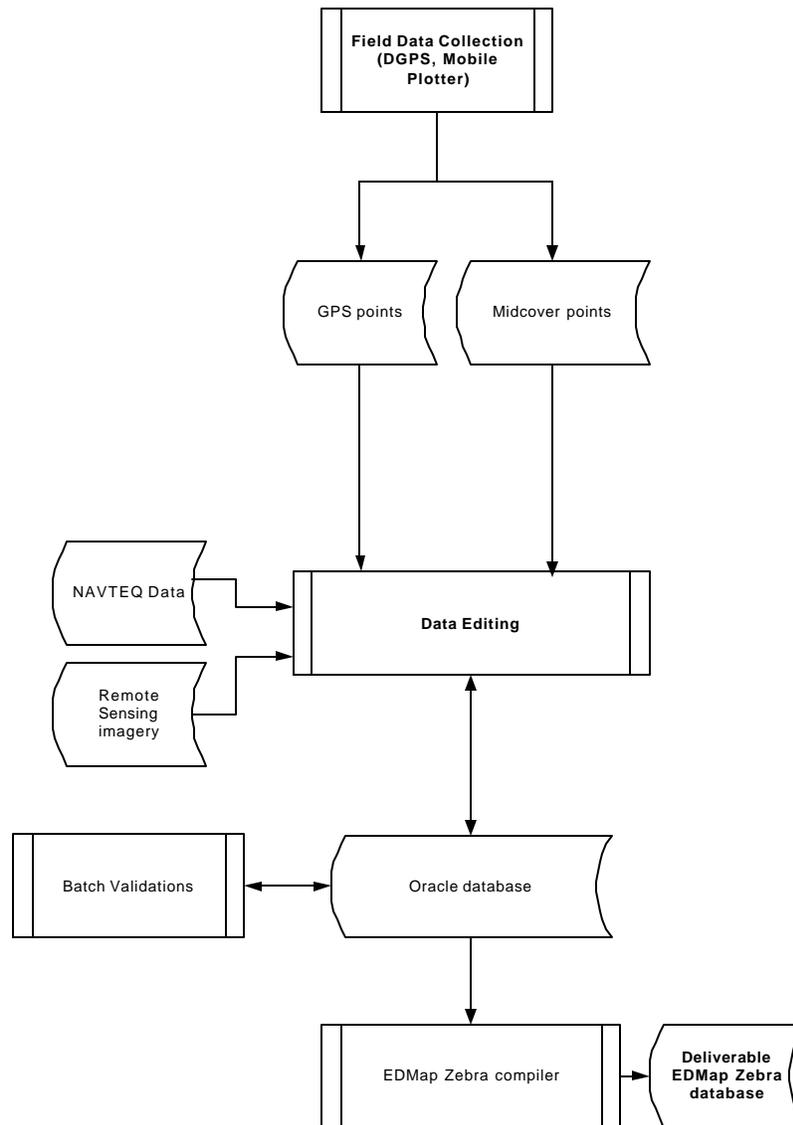


Figure 3-2: Process to illustrate near-term database creation process

Shape points were added, moved, or deleted along the GPS points to meet relative accuracy. This process helped eliminate the errors due to missing GPS points and lane changes during data collection. This process can be viewed as an averaging of GPS points into shape points.

The spline creation tool, integrated with the edit tool, generated the control points and knots to represent the shape. The editors reviewed the spline (defined by its control points and knots) in the edit tool to ensure that the shape was in line with imagery, existing link geometry, and GPS traces, as shown in Figure 3-3.

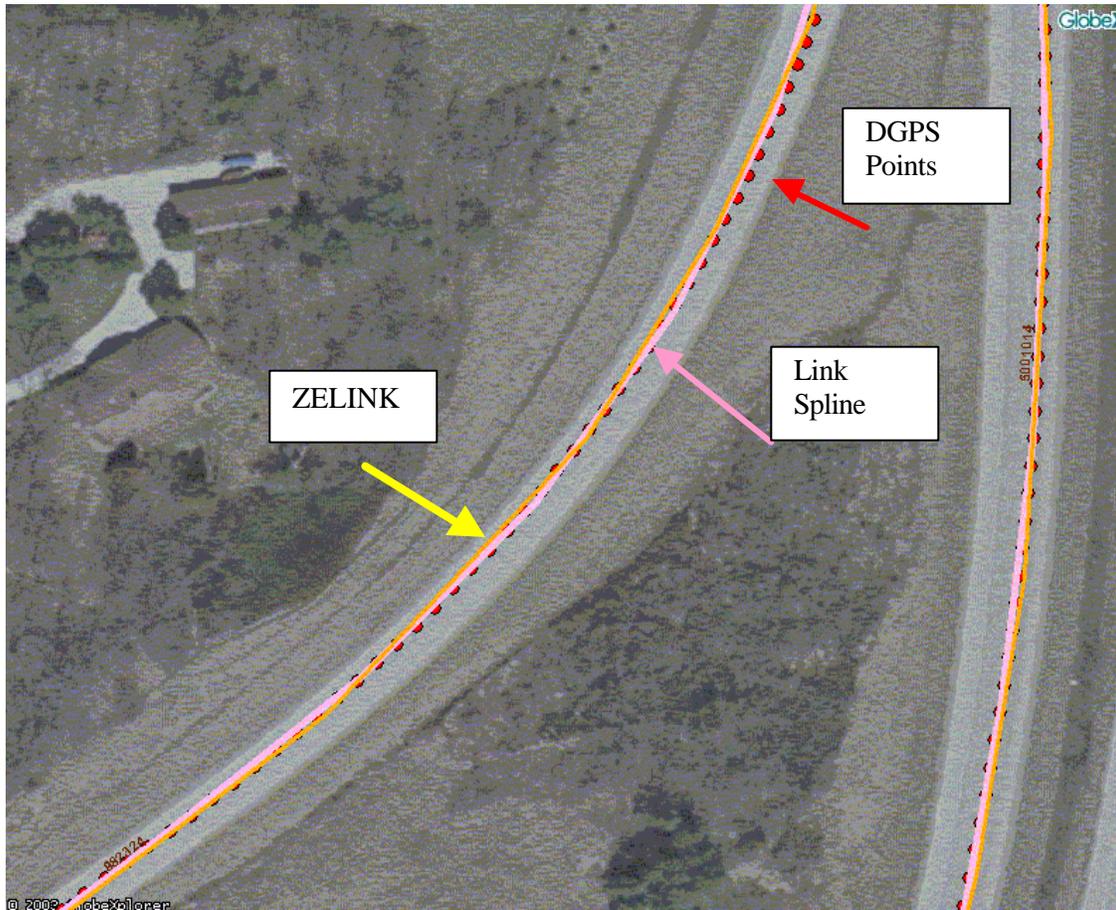


Figure 3-3: Illustration of EDMap ZELink, GPS traces, and the resulting spline

The spline tool generated a warning whenever the resulting spline deviated from a pre-set tolerance of 2m from the shape points. This in turn triggered the editor to examine, review and re-spline the geometry. This process in turn helped meet the absolute accuracy requirements for EDMap. An independent spline was created for each ZELink and the control points, knots, and shape points were stored as part of the database for each ZELink.

ADASRP delivered the control points and knots as part of link geometry. The spline was used by the application for warning/control purposes.

Delivery

Road geometry was delivered to the application as splines. ADASRP delivered the control points and knots as part of link geometry. The various EDMap applications used the spline and the attributes along the spline were used by the application for warning/control purposes.

3.2.2.2 Curvature

Curvature was one of the most important attributes for EDMap databases. For road-level spline creation, a spline-fitting algorithm was developed that attempted to closely interpolate or approximate the sparse shape points in the database. To ensure smooth road curvature, the spline-fit application was customized to ensure minimal variations in curvature while being consistent with the input data points. This functionality was the backbone of the road-level spline-fit algorithm since it controlled the shape (minimal variation in curvature) between the sparse data points.

The spline-fit algorithm for road-level spline curve creation was faced with the challenge of providing road center geometry with fair curvature. Since curvature is an intrinsic property of a curve, it is directly tied to the shape of the curve. If the shape of the curve geometry changes, so does its curvature, and vice versa. Providing good spline geometry was a challenging problem due to the following issues:

- The shape points have a relatively high positional inaccuracy due to sensor noise and accumulated errors in the repositioning process.
- Due to the sparse nature of the shape points, much of the road shape must be mathematically re-constructed between the shape points to ensure fair curvature.
- Due to the sparse nature of the shape points, it was expected that much of the spline's deviation from the road center would occur between the shape points.
- Insufficient positional constraints near the ends of road segments could lead to curvature errors at or near the ends of the splines.
- Database road center link geometry definitions and connectivity definitions impose limitations in modeling actual road center shape while maintaining fair curvature.

The goal was to develop a road-level spline-fitting tool that would ensure that the spline curve would exhibit fair curvature while still representing the road center within the accuracy requirements. This means that the resulting splines should be as smooth as possible while still representing the road center location within the requirements. Figure 3-4 illustrates the spline and curvature vectors for a road segment.

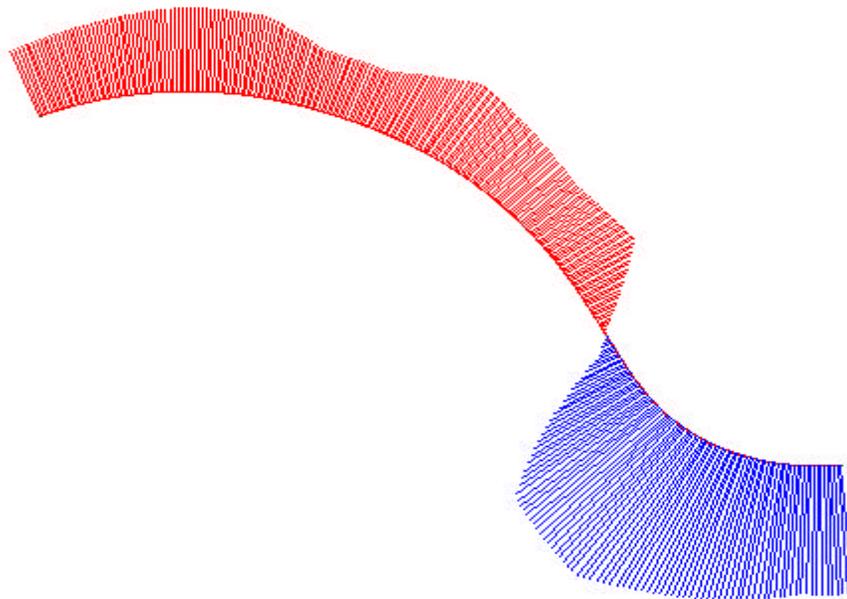


Figure 3-4: Curvature porcupines for a road segment

3.2.2.3 Point Attributes (Mobile Plotting)

During field data collection, the field analysts recorded mobile plotter events to collect point attributes along the road. These attributes include number of lanes, current lane, location of speed limit, road surface type, etc. These events are recorded during data collection according to the pre-defined guidelines for each attribute.

The output file from the mobile plotter contained the GPS timestamp and lat/long position of each event. For mid-term data collection, the positions recorded were not differentially corrected. The time stamp was used to improve the position accuracy of mobile plot events using post processed GPS locations. The mobile plotter events were then converted into a read-only ArcGIS layer and made available to the data editor. This layer was called the “midcover”. To illustrate the process, this section describes the process of collecting and creating stop sign attributes using mobile plot events.

Stop Sign Collection

Stop sign locations were collected in the field by mobile plotting. A “mobile plotter event” (data point) was captured as the car stopped at each stop sign. To achieve positional consistency, the driver stopped the car such that the GPS antenna aligned with the stop sign position. After the car came to a complete stop, the field analyst created the “stop sign” mobile plotter event.

When leaving intersections, the field analyst also passed stop signs facing oncoming traffic. These were captured by an “opposite stop” mobile plotter event. Here the car was typically being driven slowly but was not at a full stop.

Stop Sign Processing

Each stop sign event in mid-cover was created and stored as a ZEpoint object in the EDMap database. The data editor created a stop sign ZEpoint object corresponding to each stop sign in mid-cover event. Figure 3-5 shows an example of how mid-cover points are displayed on the editor's screen. The EDMap and midcover data are shown over a USGS DOQQ aerial image.

- The small dots are GPS points.
- The yellow symbols and labels represent midcover events. In addition to stop sign, there are events for yield signs, speed limit (“45 MPH”), road surface type (“concrete”), and road condition (“road uneven”) mapplets. The “no offset” and “multi dig” events indicate that the vehicle is in the actual road center (no lateral offset) of one section of a multiple-digitized roadway. Field analysts also subjectively captured “grade up” and “grade down” events to facilitate corroboration with grade data to be derived from sensors.
- The arrowheads on the links indicate the conventions used to refer to the nodes in a link. (node 0 and node 1).
- The red stop sign (and yield sign) icons represent EDMap stop and yield sign mapplets, as placed into the map database. One of the yield signs is inverted to indicate that it is “facing node 1”.

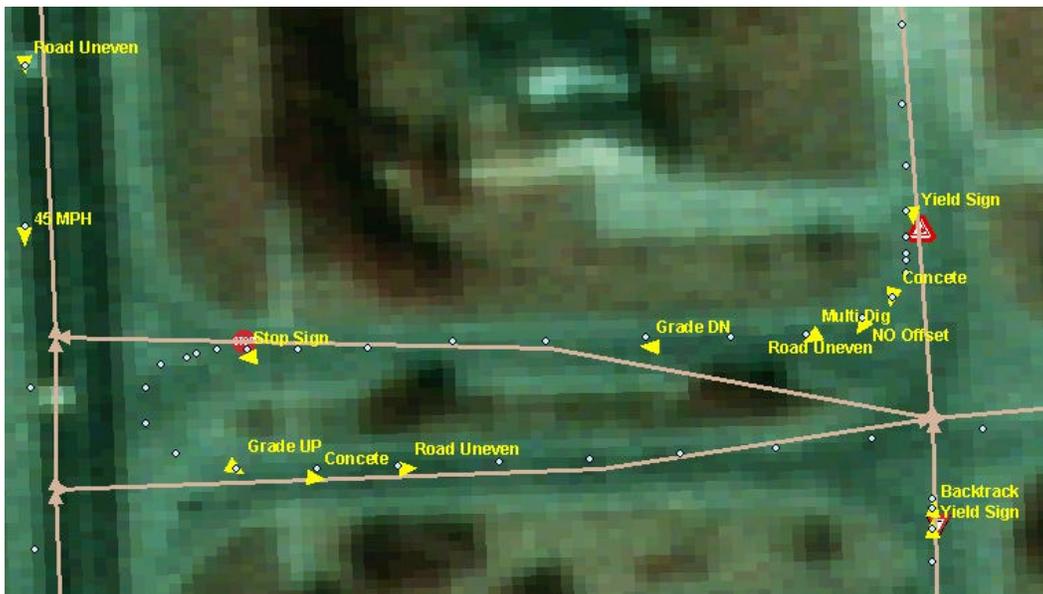


Figure 3-5: Midcover events in editor display

The edit tool associated the stop sign object with the underlying ZELink and determined its position, in centimeters, from the node 0 end of the ZELink. This enabled the EDMap applications to receive upcoming stop sign information in the ADASRP electronic horizon relative to the current vehicle position.

Stop Sign Delivery

Together with all other EDMap data, the stop sign information was extracted from an Oracle database and compiled by the EDMap Zebra compiler into a binary form usable by ADASRP. The position of a particular stop sign was derived from its underlying ZELink's geometry together with the offset position (distance from node 0 of the ZELink).

3.2.3 Mid-term Database

This section describes the components used in the mid-term data collection system and the overall process used for lane-level database creation. More details of data collection systems are described in Appendix C, Section C.1, *Mobile Mapping*. The collection and creation of lane width and traffic signal locations are also discussed to illustrate lane attribute creation.

3.2.3.1 Lane Geometry

Collection

All position traces for the mid-term database were collected using a high-end Applanix system (POS LV 420), capable of delivering cm-level positioning accuracy. Corrections from base stations in close proximity to data collection areas were also recorded and used as reference data for post processing. A total of 1 GB of Applanix raw data was collected for every four hours of drive time. The data was then transferred to a central processing location for post processing.

Position data was collected at least for the inner and outermost lanes along a route. In cases of lane ambiguity (complex interchanges, frequent lane merges, and forks), drive data was collected for all through lanes rather than just the inner and outer lanes. Lane width data was collected using a Mobileye lane-tracking system. Mobileye is a vision-based lane mark detection system using a single camera. Digital images at predefined intervals were also recorded along the drive route. Multiple computers were used to collect geometry, Applanix raw data, point attribute, lane data and images. Figure 3-6 illustrates the hardware components used in the mid-term data collection system.

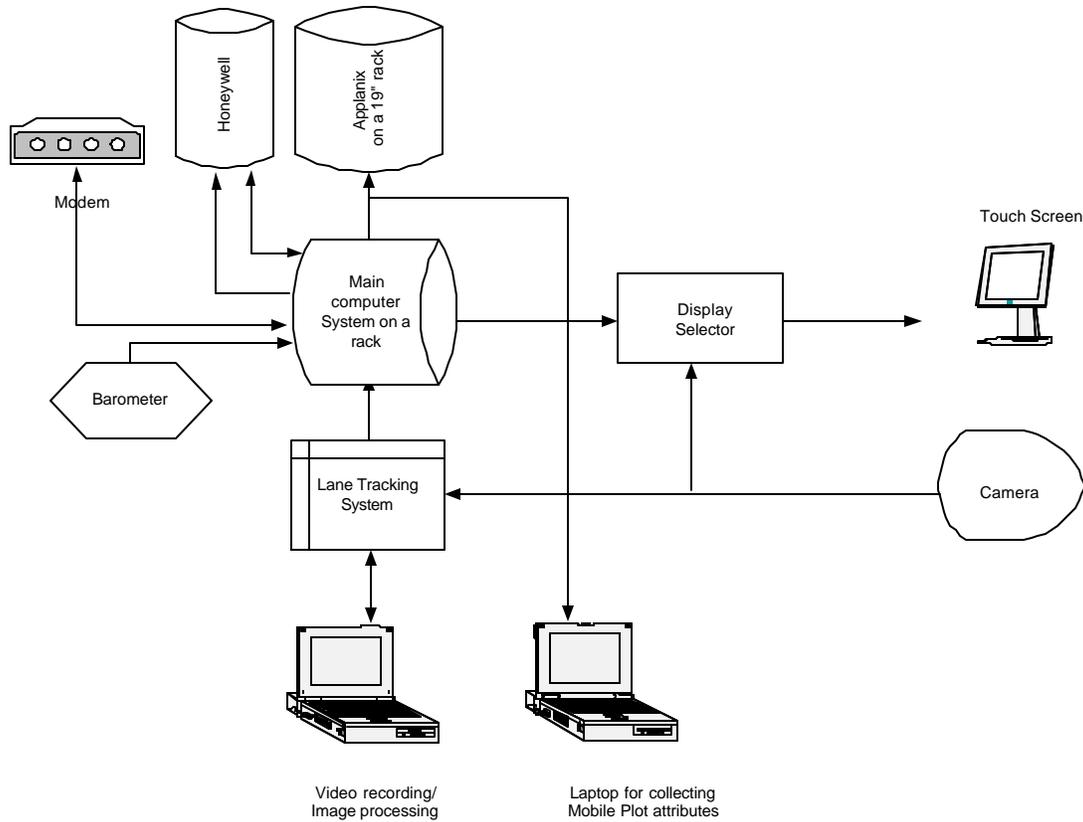


Figure 3-6: Mid-term data collection system configuration

Processing

All mid-term mapplets (geometry and attributes) were derived from post-processed Applanix position data. Base station data and Rover data were combined in the Applanix post-processing software by an experienced geodesic professional. The resulting post-processed data was used for geo-synchronization of images, lane parameters, and attributes. Figure 3-7 shows the steps involved in processing and creating mid-term lane geometry and attributes.

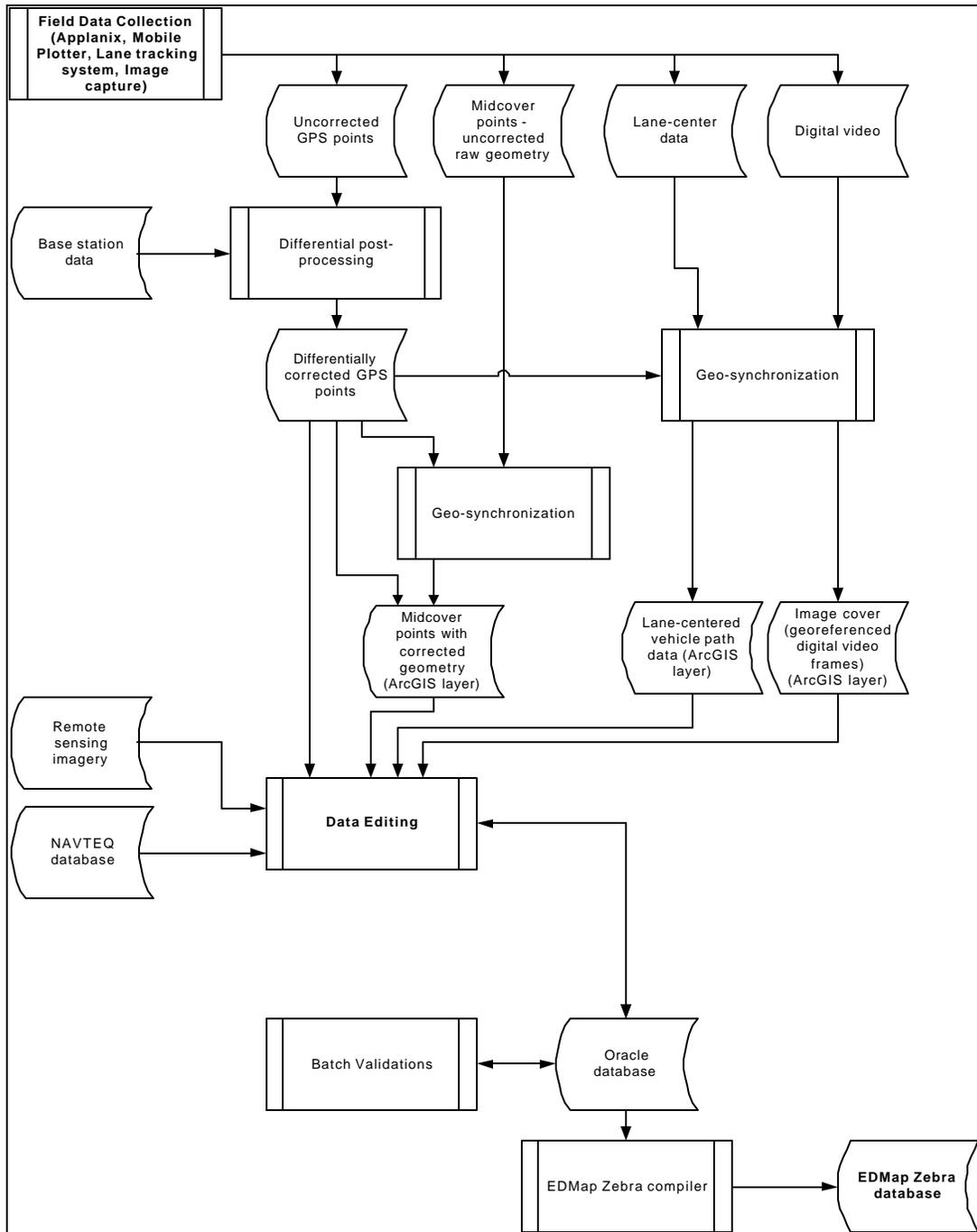


Figure 3-7: Process flow diagram for lane geometry creation

Post-processed Applanix GPS traces were fused with lane width data to generate lane centerline data using mathematical transformations. In many cases, the lane width data was not available continuously throughout a lane and was erroneous in some instances. Some of this was due to missing and confusing lane-marking information, while others were due to deficiencies in the lane tracking system. Hence, only lane data that had a high confidence measure was used for merging with GPS data.

The editors subjectively decided which input data to use for lane spline creation, based on the quality of the available centerline and GPS data. The GPS points were always available and were mostly accurate to within 20 cm of the actual driven path. The accuracy drifted between 50 cm and 1 m in challenging areas like interior Page Mill Road and Skyline Blvd. south of Palo Alto. It was also challenging to post process data for these areas.

When reliable lane width information was available, the accuracy of the lane centerline geometry further improved, which helped eliminate driver drift within a lane. Conversely, absence of reliable lane width information resulted in lane geometry being created from the “as-driven” data points, which do not reliably represent true lane centerline.

A spline-fitting algorithm, tailored to create geometry using high accuracy data, was used for lane spline creation. This algorithm was developed with an assumption that the input data was accurate, represented true lane center, and hence used a fairly dense knot vector and “loose” regularization factor that allowed the spline to pass through or very close to every data point. A spline-fit tolerance of 30 cm was used to ensure that the error introduced by the spline fitting algorithm is minimal. In some situations the input data was not as accurate as expected, and thus spline fit using post-processed Applanix GPS points resulted in wiggling and curvature distortions at the lane level, to which the lane departure warning applications was sensitive. The ability to use a stiffer spline in these cases could help reduce or eliminate the wiggling, but true lane center spline could still not be guaranteed since the as-driven path can be misaligned with respect to true lane center. Unless input data is very highly accurate, splined data inherently is a trade-off between accuracy (with respect to input data) and smoothness; the spline algorithm used opted for maximum fidelity to the input data rather than maximum smoothness.

3.2.3.2 Attributes (Lane Width)

Collection

Lane width data was collected using Mobileye a lane-tracking system. Lane tracking software was customized to report lane width as the value between the inner edges of the lane. The GPS data collection subsystem operated simultaneously with lane width collection. Continuous improvements to this system helped integrate the lane-tracking system closely with our data collection system.

Images captured using a lane-tracking system were also used for lane width attribute creation. Lane width and images were recorded in a sequence of clips to prevent data loss from unexpected system failures. Each clip was typically configured to collect 1000 JPEG images.

Processing

A two-stage merge program geo-referenced the lane data records in each clip with post-processed GPS data. The geo-referenced lane data records were converted into ArcGIS backcovers for use in the editing tool. This backcover was referred to as the Lane Path cover. This cover carried the lane attributes (lane border type, lane width, and neighboring lane data) collected at that location.

The continuous variation of lane width made it difficult to identify locations where lane width changed by a fixed number over a given distance. A stand-alone program processed the geo-referenced lane data records and generated the points of lane width change. This program identified locations where the lane width changed by more than 30 cm for a continuous stretch of 50 m. This consolidated data helped eliminate noisy

data from the lane tracking system. Another ArcGIS backcover, referred to as the lane width cover, was created using the results of this program.

Photogrammetry was used as another source to verify the lane width reported by the lane tracking system. Thus, a combination of continuous lane data, photogrammetry and consolidated lane width data was used to create the lane width attribute that meets EDMMap requirements. Figure 3-8 below illustrates all this information, as used by the data editors.

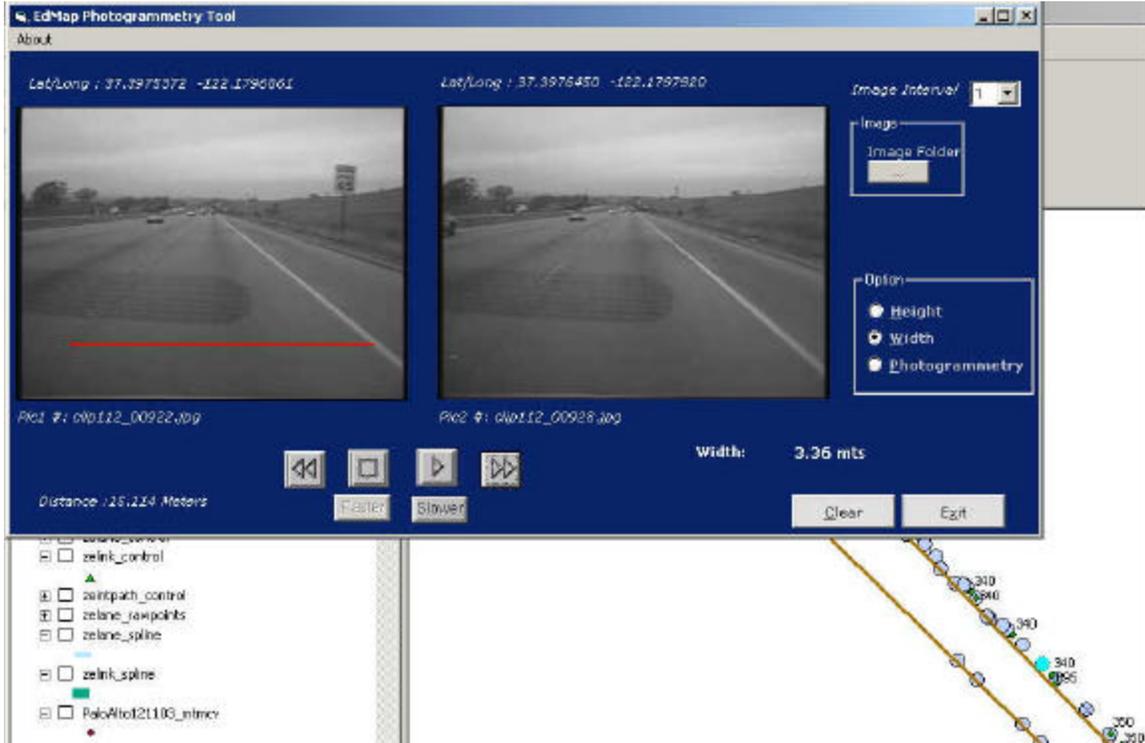


Figure 3-8: Lane width creation using multiple data sources

Delivery

Lane width can be a lane attribute or sublane attribute. Whenever the lane width for a lane changed by more than 30 cm for extended length (greater than 50 m), a sublane with a different lane width attribute was created. The sublane attribute was stored with its offset distance from node 0 of its lane. This was typical of all sublane attributes.

3.2.3.3 Point Attributes (Traffic Signal)

Collection

The primary source for traffic signal location was geo-referenced digital video captured by the Mobileye subsystem in the mid-term collection vehicle. Field analysts applied a midcover “traffic signal” event to indicate to editors that the intersection being passed had signals, but mobile plotting could not (and did not attempt to) capture the locations of individual signals.

Processing

The digital video captured by the data collection system, like other field-collected data, went through a series of preprocessing steps before it was made available to editors. Figure 3-9 shows an edit tool view with midcover and image cover points; this is the intersection of Haggerty and 12 Mile Road, Novi/Farmington Hills, Michigan, near CAMP.

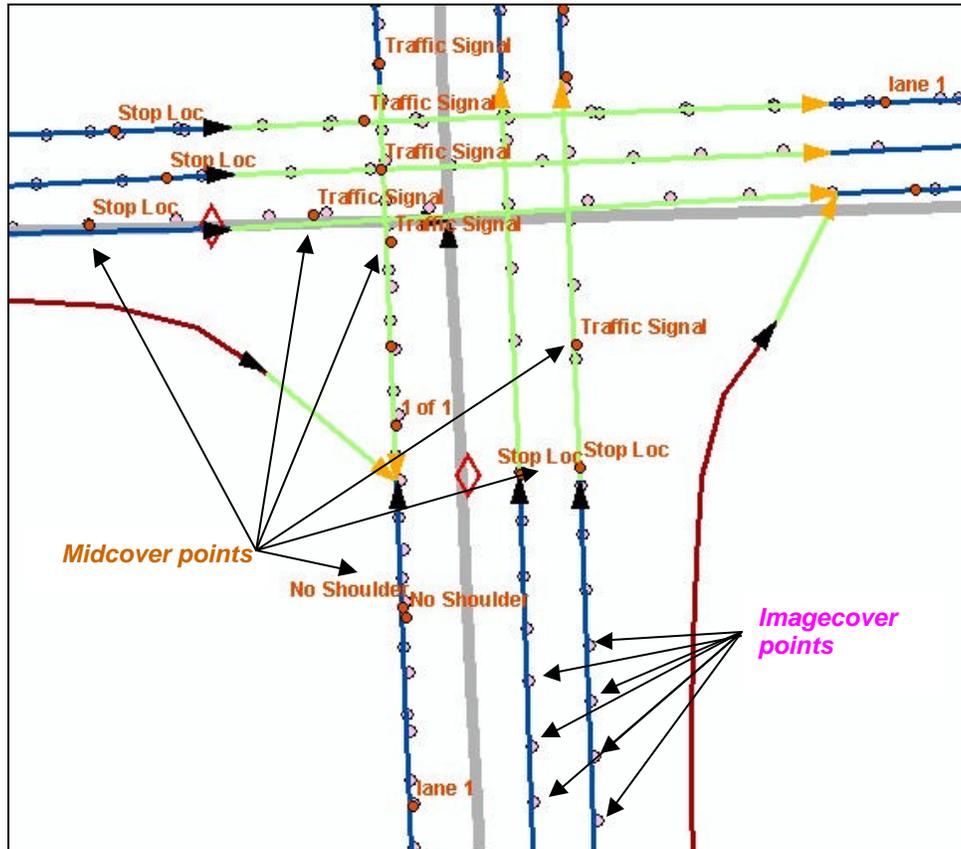


Figure 3-9: Midcover and image cover points at a signalized intersection

As can be seen from Figure 3-9, the midcover points flag the existence of traffic signals and the placement of stopping locations. Traffic signals were added to the database only after intersection coding and intersection maneuvers were completed. These were prerequisites because all traffic signals needed to be associated with intersection maneuvers.

Using the midcover as a guide, the traffic signals were added on each road segment leading into the intersection. The data editor viewed the image cover using a custom photogrammetry tool designed within ArcGIS.

The traffic signal objects were then placed into the map in one of two ways:

- Using triangulation supported by the photogrammetry tool, as shown in Figure 3-10.
- Manual placement based on the review of the images. This was adopted whenever the photogrammetry solution was unable to compute the correct traffic signal location. This happens due to small viewing angle differences or not being able to view the same object in consequent frames.



Figure 3-10: Traffic signal placement by triangulation

After placing the traffic signals at an intersection, the signals were “clustered” to combine multiple signals controlling the same maneuvers. These clusters were associated with the intersection maneuver(s) controlled by this signal cluster. Generally, for any given intersection, all (or none) of the intersection maneuvers present were associated with traffic signal clusters.

Delivery

Together with all other EDMap data, the traffic signal information was extracted from an Oracle database and compiled by the EDMap Zebra compiler into a binary form usable by ADASRP. Unlike other point objects (stop signs, yield signs, etc.), the position of a particular traffic signal delivered to applications was the actual lat/long as determined in the edit tool.

Based on the intersection maneuvers and traffic signal clustering, the EDMap Zebra compiler associated each traffic signal with the lane(s) to which it applied. Thus an application could receive the pertinent traffic signal information appropriate to the actual lane the vehicle currently was traversing. This helps the application to determine which traffic signal is applicable to the vehicle, based on their current lane to which it is currently matched.

3.3 Deployment Constraints and Potential Mitigations by Application

3.3.1 Maintainability

Roads and their characteristics in the real world inevitably change, and these changes result in map inaccuracies until the map is updated to match reality. These inaccuracies can diminish the effectiveness of EDMap applications. This section will discuss some possible concepts to help mitigate these problems. (A further discussion on the ways that maps can become inaccurate is included Appendix C, Section C.5, *Maintainability*.)

Different EDMap applications will have different sensitivities to map staleness and degradation, based on the critical mapplets for each application. Overall road shape and road grade will rarely change. Individual lane positions are somewhat likely to change, such as during road repairs, even on a temporary basis. Over time, stop signs are likely to be added, though stop signs are rarely removed or relocated. Similarly, traffic signals are also likely to be added over time, and are more likely than stop signs to be reconfigured. Roadside barriers and overhead objects will change infrequently.

3.3.1.1 Timely Acquisition of Data

The first step in keeping EDMap maps current is the awareness that a change has taken place. The maintainability discussion in Appendix C, C.5, *Maintainability* describes the types of changes which can take place, and the methods available to detect these changes. The primary challenge in most of these methods is timeliness. The methods with the greatest promise to deliver very timely information regarding change are probe vehicle techniques, and leverage leveraging of traffic reporting systems (primarily for “acute” change).

Analysis of basic probe data (a time-stamped sequence of vehicle locations) can provide information not only about road (and potentially) lane geometry, but also intersection maneuver patterns, presence of stop signs, presence of traffic signals, empirical stopping locations for stop signs or traffic signals, and effective speeds. Continuous analysis of probe data could thus detect temporary or permanent changes in any of these attributes, though some attributes (such as traffic signals) will require additional data collection before the map can be updated. Farther into the future, probe data containing additional data from the probe vehicles could contribute to other EDMap mapplets; this data could include vehicle dynamics, imagery, or other sensor data. Even basic information such as turn signal usage could be of value when analyzing probe data.

Traffic reporting systems are another means of acquiring acute changes on the road, such as lane closures or detours, on a very timely basis. These systems are becoming integrated with navigation now in certain major metropolitan areas.

3.3.1.2 Map Updates

Once a change has been detected, and the map database updated, the updated map still needs to be deployed into the vehicle.

Current commercial-scale map databases are updated and delivered periodically. Digital map customers (such as OEMs or application builders) have various needs; Depending on customer needs, the delivery can be an “extract” (such as a plain-text GDF, Geographic Data File, format), or a compiled database (such as NAVTEQ SDAL format). Customers receiving extracts typically compile the extracts into a proprietary format, further slowing deployment.

The industry is migrating toward a more real-time update and delivery infrastructure, improving capabilities in the core database repository, compilation, and delivery. The EDMap project pioneered use of the new compilation format, “Zebra”, NAVTEQ’s successor to SDAL. Key advantages of emerging database infrastructures include the ability to release updates much more frequently, and independence from set coverage area boundaries. Use of Zebra is an important enabling step for higher-frequency data updates.

Still, the EDMap test applications were dependent on deliveries of entire databases, delivered online or in CD-ROMs, and kept on board the vehicle. Real deployment of EDMap applications will benefit from the ability to access a frequently updated map database, either as an “off-board” system (data on a server) or as a “hybrid” system, where the core map is in the car but recent changes are available from a server.

3.3.2 Limitations and Constraints

3.3.2.1 Availability of Probe Data

As promising as probe data is for enabling timely data acquisition, obstacles need to be overcome before probe data can be a reliable source.

Probe vehicle data to some extent is a “chicken-and-egg” situation. There is no value in outfitting a multitude of vehicles as probes until there is a tangible benefit from doing so, but at least some of those benefits cannot come to fruition without a meaningful deployment of probes on the road. A discussion on the practical means of establishing a critical mass of probe vehicles is outside the scope of EDMap, but it is reasonable to expect that as probe data becomes available it will be a key component of keeping enhanced maps as timely as possible.

Key challenges to overcome before probe data will be generally available include:

- **Communications:** transmission of data from probe vehicles to data aggregators.
- **Ownership and access:** Who will own data obtained from privately owned vehicles, fleets of vehicles, or public vehicles, and how will this data be made available for analysis?
- **Data storage:** Management of tremendous volumes of raw data.
- **Privacy:** Concerns about real or perceived potential to misuse vehicle location data, particularly personally identifiable data.
- **Accuracy:** Low-cost probe devices will not necessarily provide lane-level geometry at accuracy levels required by some EDMap applications.
- **Costs:** Who pays the costs of deploying probe equipment, providing communications, or enhancing probe equipment with further capabilities, and how are these costs recouped?

3.3.2.2 Availability of Other Sources

High-quality aerial imagery was found to be useful for placing and verifying several attributes (e.g., painted stopping locations are readily visible, lane configurations can be verified, and 2-D placement of attributes such as signs and traffic signals present in digital video can be confirmed). At present, highest-quality imagery is more likely to be available in more heavily populated areas, but less so elsewhere. The ubiquitous USGS DOQQs are of some, but limited, value for EDMap map creation.

3.3.2.3 Ability to Communicate Map Updates

Rapid delivery of updated maps to EDMap applications requires fundamental changes to the ways that maps are distributed and used. The method used in the test databases, with the entire map on-board in the vehicle, is not conducive to frequent change. Off-board or hybrid methods will be essential for mapplets that have strict demands for data freshness. Appendix J, Section J.5 describes two technologies with the potential to deliver map updates wirelessly to vehicles.

3.3.2.4 Production-level Edit Environment Development

Estimates for relative effort to produce EDMap databases were based on a conceptual model of production-level editing tools. The EDMap test databases were made with a provisional tool set which, while capable of creating the EDMap mapplets, has performance substantially below that of NAVTEQ proprietary tools. This provisional toolset will not scale well to larger projects. Therefore, in order to deliver map databases with the relative effort outlined in this report, a software development effort will need to be undertaken to produce an appropriate editing tool. This software development effort will need to take place before large-scale EDMap database creation begins.

In addition to performance concerns, a production-level editing tool set will employ a substantially more robust set of validations than was possible in the provisional tool set. During the evaluation of EDMap test maps, much knowledge was gained regarding ways to assess and improve data quality. A suite of batch-level validations was devised and employed to identify unusual or inconsistent data situations; these validations were very helpful in improving the final maps. Additional tools were developed to help assess and improve curvature fairness and contiguity. To the extent possible, all of these validations and assessments should be built into a production-level editing tool set. Improving quality as data is created will ensure higher quality deliverables and, by reducing or eliminating repairs and rework, reduce the overall effort required.

3.3.2.5 Data Modeling Changes

The EDMap test maps were designed around two inclusion levels: a road-level map (“WhichRoad”) and a lane-level (“WhereInLane”) map. In the course of analyzing project results, an intermediate level (“WhichLane”) was conceived. In order for a WhichLane map to fulfill application needs, some mapplets that had been planned to be at a lane level would have to be remodeled at the road level. These include:

- Roadside barriers, currently modeled as a lane or sublane attribute. These would have to be recoded as a side-specific road (link or sublink) attribute. Barriers between parallel lanes on the same road would not be capable of being modeled.
- Shoulders, currently modeled as a type of “lane adjacency.” These also would have to be recoded as a side-specific road (link or sublink) attribute. There should be no loss of capability, presuming that every road would be digitized separately in each direction for a WhichLane map.
- Enough information will need to be provided about the various lanes on a roadway, such as their lateral offset from centerline of the lane that is stored in the database, to enable an application to determine which lane is being traversed.

3.3.2.6 Resource Contention

Finally, if a large project on a nationwide scope is undertaken, map makers will need to negotiate and prioritize resources against other demands on field and production staff. The NAVTEQ field staff in the United States is responsible for maintaining current maps continuously, and expanding detail-level coverage. NAVTEQ production staff is responsible for map production not only in the United States, but worldwide.

Large-scale projects with nationwide impact are not unprecedented. A recent NAVTEQ effort to establish full coverage throughout the contiguous states was a full-time task for the whole U.S. field staff for a year, with some staff continuing work for another half year. This consumed roughly 200 person-years of field effort over 18 months, plus another 25 to 30 person-years of production effort. Clearly, projects of this magnitude require a profound commitment of time, people and money, commitment of which requires a very compelling business case.

It is possible that scheduling and cost-justification of large projects such as this can benefit from coordination with other creation and updating work. Coordinating EDMap commercial-scale development with other new or modernizing ventures could reduce the cost and duration of the project.

3.4 Database Creation Effort

Section 3.2 covered details of the process to create and deliver the mapplets specified by the EDMap applications. In a complementary manner, Chapter 2, Applications and Mapplet *Evaluation Results* described the performance of the mapplets used in each of the applications. As was seen in these two chapters, application development and evaluation occurred simultaneously in several instances with map database process improvements. Map collection and edit processes that were thought to be sufficient for mapplet delivery were found to need improvement. Likewise, in the development and implementation of vehicle applications, mapplet requirements were adjusted and revised based on application performance needs, and mapplet availability.

This section focuses on an application-by-application map database creation and delivery effort estimate based on the mapplets identified in Chapter 2, *Applications and Mapplet Results*.

Previous analyses evaluated the relative effort to create road-level and lane-level databases as compared to currently produced navigation level databases (Task 4). This relative effort estimation was based on road-level and lane-level databases containing mapplets that encompassed all demonstrated applications collectively. Effort estimates were broken down further by major components in the database production and delivery process—collection, processing (editing), and distribution.

The Task 4 result as estimated in April 2003, shown in Figure 3-11, shows the distribution within each pie chart reflecting the proportion of collection, processing, and distribution for navigation, near-term, and mid-term efforts. Results of Task 4 indicated that the operating effort to collect, process, and distribute near-term databases as an extension of navigation databases was estimated at about 25% more effort than the creation of navigation level databases using the mobile mapping techniques in use today for the production of navigation databases. In other words, the effort to build a database with the database specification of a navigation level database plus the specification for the near term applications would require 25% more effort than building to the navigation specification alone.

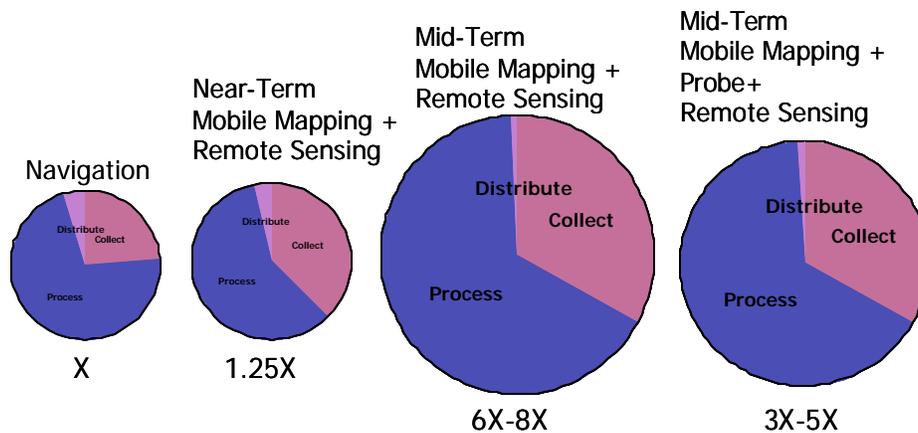


Figure 3-11: Proportion of collection, processing, and distribution for navigation, near-term, and mid-term efforts determined in Task 4 (April 2003)

However, moving to lane-level databases represents a step increase in database complexity and accuracy requirements, which are directly reflected in the relative effort to create these databases. A new data model and new representations for road curvature were developed to accommodate mid-term database requirements. New processes had to be developed and prototyped for mid-term database production, as well as the development of new skills for personnel executing the process.

Using mobile mapping as the primary method for collecting mid-term data, the corresponding effort to process and edit the collected mid-term data represents 6 to 8 times the effort of creating today's navigation level databases. This increase in effort represents 8 to 10 times the data collection and 5 to 6 times the data processing effort when compared to navigation level databases. Rough estimates indicate that the use of probe data may decrease the cost of mid-term databases to 3 to 5 times the effort of navigation databases. The reduction in effort could potentially come from a 20 to 50% decrease in the mid-term mobile mapping collection effort and a 25 to 40% decrease in the mid-term processing effort.

The takeaway information from the pie charts was that the road-level based maps were indeed near-term, but that the lane-level effort multipliers were prohibitively high. Keeping in mind that the pie charts reflect the effort level for all demonstrated applications, looking at the incremental effort for each application may be useful. This section examines the mapplet requirements by application and estimates the commercial viability of a database constructed specifically for the target application. The mapplet analysis by application has been detailed in Chapter 2. The remainder of this section considers each application database specification and the effort required to create such a database compared to the effort to create a navigation level database.

3.4.1 Curve Speed Assistant (CSA-W)

Refer to Chapter 2, *Applications and Mapplet Evaluation Results* for a description of this application.

Based on the mapplets actually needed, CSA-W needs only those attributes that are currently provided in navigation-level databases plus parametric curvature and grade. The only additional editing that would be necessary is for the creation of road-level splines, which will be a nearly automated process.

3.4.1.1 Application Mapplets

The following mapplets were determined as needed for this application:

Table 3-1: CSA-W mapplet requirements

Mapplets	CSA (W)	
	Ford	GM
Road Geometry	5 m	5 m
Road Curvature	15%	Current curvature not dependable for warning
Road Class	Not used	Useful to know to inhibit/resume operation (e.g., ramp, freeway, etc.)
Road Grade	Min 2 % (Is it above or below a certain level)	Need to know if it is above 5% or not?
Road Surface Type	Not needed	Paved/unpaved
Speed Limits	Useful; can be relaxed to 20 m accuracy	Useful; can be relaxed to 20 m accuracy
Superelevation	Is it above a certain value	Is it greater than 3%
Link Bearing Angles	Current NAVTEQ spec	

Refer to Section 3.2, *EDMap Database Creation* for a detailed description of collection, processing and delivery methods for each mapplet and Chapter 2, *Applications and Mapplet Evaluation Results* for the performance of the mapplets used in each of the applications.

3.4.1.2 Database Effort Summary

Based on the mapplets actually needed, CSA-W needs only the attributes that are (will be) present in future navigation databases, plus parametric curvature and grade. The creation of road-level splines is the only EDMap-type editing that would be necessary.

Operating Effort

Table 3-2: CSA-W database effort summary

CSA-W (RoadLevel App)	Navi DBRelative Effort	Effort (Multiples of Nav DB)	Proportion of Total Process	Weighted Effort	Proportion of Total Weighted Effort
Collection	1	1.00	0.22	0.22	0.08
Processing	3	3.45	0.74	2.56	0.92
Distribution	0.2	0.20	0.04	0.01	0.00
Totals	4.2	4.65	1.00	2.78	1.00
Effort Relative to Navi DB		1.11			

The road-level version of this application would require an approximately 10 to 15% effort above the current navigation level database, with approximately 8% of the effort in data collection and 92% in processing.

Fixed Cost

The equipment cost to collect and edit this data is covered within the equipment for the production of navigation level databases.

3.4.2 Stop Sign Assistant-W (SSA)

Refer to Chapter 2, *Applications and Mapplet Evaluation Results* for a description of this application.

3.4.2.1 Application Mapplets

The following mapplets were determined as needed for this application:

Table 3-3: SSA-W mapplet requirements

Mapplets	SSA (W)
Road Grade	Not used; need to know if it is greater than 5%
Stop Sign Location	Need either stop sign OR stopping location
Stopping Location	1 m is too stringent; need +1 m (late) and -5 m (earlier) than stop sign/location
Yield Sign Location	Valuable; 5 m is good

Refer to Section 3.2, *EDMap Database Creation* for a detailed description of collection, processing and delivery methods for each mapplet and Chapter 2, *Applications and Mapplet Evaluation Results* for the performance of the mapplets used in each of the applications.

3.4.2.2 Database Effort Summary

Operating Effort

Table 3-4: SSA-W database effort summary

SSA-W	Navi DB	Effort	Proportion of Total Process	Weighted Effort	Proportion of Total Weighted Effort
(RoadLevel App)	Relative Effort	(Multiples of Nav DB)			
Collection	1	1.8	0.33	0.59	0.21
Processing	3	3.45	0.63	2.18	0.78
Distribution	0.2	0.2	0.04	0.01	0.00
Totals	4.2	5.45	100%	2.79	1
Effort Relative to Navi DB		1.30			

The nearly double collection effort is primarily due to the need to drive every road in each direction. The road-level version of this application would require approximately 30% effort above the current navigation level database, with approximately 20% of the effort in data collection and 80% in processing.

Fixed Cost

The equipment cost to collect and edit this data is covered within the equipment for the production of navigation level databases.

3.4.3 Curve Speed Assistant (CSA-C)

Refer to Chapter 2, *Applications and Mapplet Evaluation Results* for a description of this application.

3.4.3.1 Application Mapplets

The following mapplets were determined as needed for this application:

Table 3-5: CSA-C mapplet requirements

Mapplets	CSA (C)
Lane Geometry	1 m required for lane level positioning
Lane Curvature	Relaxed to 10%
Road Grade	1% increments
Road Surface Type	Paved/unpaved
Road Class	inhibit/resume
Stopping Location	Helpful but not required

Refer to Section 3.2, *EDMap Database Creation* for a detailed description of collection, processing and delivery methods for each mapplet and Chapter 2, *Applications and Mapplet Evaluation Results* for the performance of the mapplets used in each of the applications.

3.4.3.2 Database Effort Summary

Operating Effort

The editing effort for this database was determined by looking at the ten steps of the edit process and determining which steps would be required for this application database. Using this information and the actual effort data for each step recorded during the database creation work, an editing effort factor was created for each database.

Note that a need for lane geometry requires more than just the Lane Geometry Creation phase; adjacencies, lane types, and intersections are all needed to enable correct preview based on lane placement.

There is some reduction in edit effort due to the reduced mapplet list. The editing effort is estimated at 64% of the effort for full mid-term database editing.

The effort to create this application-specific database is reflected in the following table.

Table 3-6: CSA-C database effort summary

CSA-C	Nav DB	Effort	Proportion of Total Process	Weighted Effort	Proportion of Total Weighted Effort
(Lane-level App)	Relative Effort	(Multiples of Nav DB)			
Collection	1	4	0.25	0.99	0.10
Processing	3	12	0.74	8.89	0.90
Distribution	0.2	0.2	0.01	0.00	0.00
Totals	4.2	16.2	100%	9.88	1
Effort Relative to Nav DB		3.86			

The lane-level version of this application would require approximately 4 times the effort relative to the current navigation-level database, with approximately 10% of the effort in data collection and 90% in processing.

Since this application works well with lane-level data when the vehicle path approaching a bifurcation is known, an alternate database solution would be to provide lane information only when approaching bifurcations or ramps. This would reduce the lane data editing cost to about one-third of the editing for providing lane-level information everywhere.

The effort to create this application specific database is reflected in the following table:

Table 3-7: CSA-C database effort summary with fewer lanes

CSA-C Fewer Lanes	Navi DB	Effort	Proportion of Total Process	Weighted Effort	Proportion of Total Weighted Effort
(LaneLevel App)	Relative Effort	(Multiples of Nav DB)			
Collection	1	4	0.49	1.95	0.50
Processing	3	4	0.49	1.95	0.50
Distribution	0.2	0.2	0.02	0.00	0.00
Totals	4.2	8.2	100%	3.91	1
Effort Relative to Navi DB		1.95			

The reduced lane-level version of this application would require approximately twice the effort relative to the current navigation level database, with approximately 50% of the effort in data collection and 50% in processing.

Fixed Cost

The collection of high accuracy lane-level geometry requires the use of currently high cost equipment, such as a high precision Applanix or Honeywell INS. These systems cost in excess of \$100K today, making widespread deployment of a fleet of so equipped vehicles cost prohibitive.

3.4.4 Forward Collision Warning (FCW-W)

Refer to Chapter 2, *Applications and Maplet Evaluation Results* for a description of this application.

3.4.4.1 Application Mapplets

The following mapplets were determined as needed for this application:

Table 3-8: FCW mapplet requirements

Mapplets	FCW
Lane Geometry	Need lane level accuracy as defined
Road Grade	Not evaluated; keep original requirements
Road Surface Type	Paved/unpaved
Intersection Location	Useful; relax to 10 m
Road Class	Useful to Inhibit/resume operation (e.g., freeway, ramp, etc.)
Intersection Location	Useful; relax to 10 m
Stationary Roadside Barriers	Guard rails <2 m from road edge needed; can be a road (near-term map) attribute
Overhead Stationary Roadway Barriers	Useful on roads that exhibit grade; can be a road (road-level map) attribute

Refer to Section 3.2, *EDMap Database Creation* for a detailed description of collection, processing and delivery methods for each mapplet and Chapter 2, *Applications and Maplet Evaluation Results* for the performance of the mapplets used in each of the applications.

3.4.4.2 Database Effort Summary

Operating Effort

The editing effort for this database was determined by looking at the ten steps of the edit process and determining which steps would be required for this application database. Using this information and the actual effort data for each step recorded during the database creation work, an editing effort factor was created for each database.

The effort to create this application specific database is reflected in the following table:

Table 3-9: FCW-W database effort summary

FCW-W	Navi DB	Effort	Proportion of Total Process	Weighted Effort	Proportion of Total Weighted Effort
(LaneLevel App)	Relative Effort	(Multiples of Nav DB)			
Collection	1	4	0.23	0.93	0.09
Processing	3	13	0.76	9.83	0.91
Distribution	0.2	0.2	0.01	0.00	0.00
Totals	4.2	17.2	100%	10.76	1
Effort Relative to Navi DB		4.10			

The lane-level version of this application would require approximately 4 times the effort relative to the current navigation-level database, with approximately 9% of the effort in data collection and 91% in processing.

Fixed Cost

The collection of high accuracy lane-level geometry requires the use of currently high cost equipment, such as a high precision Applanix or Honeywell INS. These systems cost in excess of \$100K today, making widespread deployment of a fleet of so equipped vehicles cost prohibitive.

3.4.5 Lane Following Assistant (LFA-W)

Refer to Chapter 2, *Applications and Mapplet Evaluation Results* for a description of this application.

3.4.5.1 Application Mapplets

The following mapplets were determined as needed for this application:

Table 3-10: LFA mapplet requirements

Mapplets	LFA
Lane Geometry	Accuracy + Lane Width stays same; eliminate relative accuracy requirement.
Lane Width	Same as above
Transition Zone	Used as currently delivered to reduce false alarms (additional mapplet)
Adjacency Mapplet	
Shoulder Width	Is it < 0.5 m or > 0.5 m
Adjacency Mapplet	
Road Grade	Not evaluated, keep original requirements
Road Surface Type	Paved/unpaved
Road Class	Inhibit/resume operation (e.g., freeway, ramp, etc.)
Intersection Location	Relax to 10 m

Refer to Section 3.2, *EDMap Database Creation* for a detailed description of collection, processing and delivery methods for each mapplet and Chapter 2, *Applications and Mapplet Evaluation Results* for the performance of the mapplets used in each of the applications.

3.4.5.2 Database Effort Summary

Operating Effort

The effort to create this application specific database is reflected in the following table:

Table 3-11: LFA database effort summary

LFA (LaneLevel App)	Navi DB Relative Effort	Effort (Multiples of Nav)	Proportion of Total Process	Weighted Effort	Proportion of Total Weighted
Collection	1	4.00	0.23	0.93	0.09
Processing	3	13.00	0.76	9.83	0.91
Distribution	0.2	0.20	0.01	0.00	0.00
Totals	4.2	17.20	1.00	10.76	1.00
Effort Relative to Navi DB		4.10			

The lane-level version of this application would require approximately 4 times the effort relative to the current navigation level database, with approximately 9% of the effort in data collection and 91% in processing.

Fixed Cost

The collection of high accuracy lane-level geometry requires the use of currently high cost equipment, such as a high precision Applanix or Honeywell INS. These systems cost in excess of \$100K today, making widespread deployment of a fleet of so equipped vehicles cost prohibitive.

3.4.6 Traffic Signal Assistant (TSA-W)

Refer to Chapter 2, *Applications and Mapplet Evaluation Results* for a description of this application.

3.4.6.1 Application Mapplets

The following mapplets were determined as needed for this application:

Table 3-12: TSA-W mapplet requirements

Mapplets	TSA-W
Stopping Location	Relax to 3 m for warning
Traffic Signal Location	Longitudinal accuracy 3 m and Lateral accuracy 2 m; absolute height might be useful
Lane Geometry	Need lane level accuracy as defined

Refer to Section 3.2, *EDMap Database Creation* for a detailed description of collection, processing and delivery methods for each mapplet and Chapter 2, *Applications and Mapplet Evaluation Results* for the performance of the mapplets used in each of the applications.

3.4.6.2 Database Effort Summary

Operating Effort

The effort to create this application specific database is reflected in the following table:

Table 3-13: TSA-W database effort summary

TSA-W	Navi DB	Effort	Proportion of Total Process	Weighted Effort	Proportion of Total Weighted Effort
(LaneLevel App)	Relative Effort	(Multiples of Nav DB)			
Collection	1	4.00	0.39	1.57	0.31
Processing	3	6.00	0.59	3.53	0.69
Distribution	0.2	0.20	0.02	0.00	0.00
Totals	4.2	10.20	100%	5.10	1.00
Effort Relative to Navi DB		2.43			

The lane-level version of this application would require approximately 2.5 times the effort relative to the current navigation level database, with approximately 31% of the effort in data collection and 69% in processing.

Fixed Cost

The collection of high accuracy lane-level geometry requires the use of currently high cost equipment, such as a high precision Applanix or Honeywell INS. These systems cost in excess of \$100K today, making widespread deployment of a fleet of so equipped vehicles cost prohibitive.

3.4.7 Stop Sign Assistant (SSA-C)

Refer to Chapter 2, *Applications and Mapplet Evaluation Results* for a description of this application.

3.4.7.1 Application Mapplets

The following mapplets were determined as needed for this application:

Table 3-14: SSA-C mapplet requirements

Mapplets	SSA (C)
Road Grade	Useful only if it is > 5%
Road Surface Type	Paved/unpaved
Stop Sign Location	Need 1 m accuracy
Stopping Location	Need 1 m accuracy
Yield Sign	Keep original requirement

Refer to Section 3.2, *EDMap Database Creation* for a detailed description of collection, processing and delivery methods for each mapplet and Chapter 2, *Applications and Mapplet Evaluation Results*, for the performance of the mapplets used in each of the applications.

3.4.7.2 Database Effort Summary

Based on application analysis, having lane-level information does not benefit this application. The required mapplets (stop signs, stopping locations, and road geometry) are all included in near-term mapplets. Lane information was not necessary, and it is reasonable to consider the SSA-W effort as being valid for SSA-C (vehicle positioning needs to be better than current navigation systems).

3.4.8 Revised Effort Summary

Table 3-15 summarizes the applications by type (WhatRoad, WhichLane or WhereInLane) and by the relative effort multiplier.

Table 3-15: Relative Mapplet Set Effort Multipliers by Application

Application Type	Application	Effort Multiplier (relative to Nav DB)	Relaxed Multiplier (relative to Nav DB)
WhatRoad	CSA-W	1.10	-
	SSA-W	1.30	-
WhichLane	CSA-C	3.86	1.95
	FCW	4.10	
	SSA-C	-	1.30
	TSA-W	2.43	-
WhereInLane	LDW	4.10	-

Breaking down relative effort by application provides an interesting slice through the range of road- and lane-level maps. It is now possible to "pick and choose" an application by effort multiplier and to then evaluate the potential safety benefit. Another significant outcome is the relaxed multiplier for CSA-C and SSA-C that results in significantly lower multipliers for the map. In the case of CSA-C, constructing lane-level representations only where there are multiple lanes, and reverting to road level elsewhere, reduces the multiplier by almost 50%. For SSA-C, the application evaluation showed that the road level mapplets were sufficient for control, and that lane-level representations were not necessary. Vehicle positioning requirements, however, to the WHICHLANE level are not relaxed.

The database creation efforts analyzed as part of Task 4 were reviewed to incorporate new experience gained during Task 7. The most notable change is in a reduction to the projected collection costs for lane-level databases, reducing from a 9times multiplier over navigation level to a 4 to 6 times multiplier. This change reduces the overall effort for the lane-level composite database from 6 to 8 times to 5 to 7 times. The collection effort for road-level databases was not affected by this change in lane-level collection estimates. Also, previous estimations regarding the effect of using probe vehicle data were not analyzed, since the data creation experiences did not include probe data. However, experience has now indicated that road-level collection of stop signs will require driving roads in both directions. This increased cost is reflected in the charts below, increasing the projected near-term increase from .25X to .35X.

The updated, relative database creation efforts with this updated information are shown in the Figure 3-11. The distribution within each pie chart reflects the proportion of collection, processing, and distribution for navigation, near-term, and mid-term. Probe data was not used for the creation of the test databases and therefore was not re-estimated.

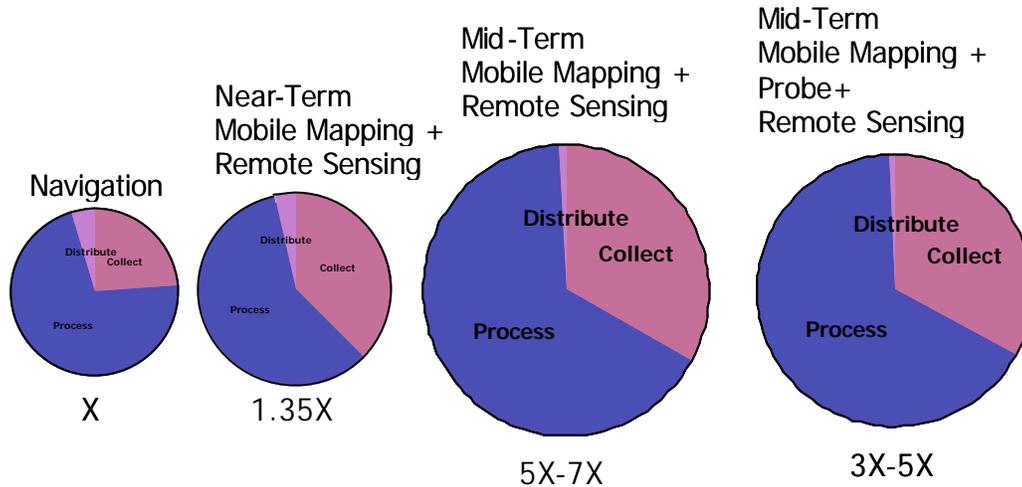


Figure 3-12: Relative database creation efforts (March 2004)

3.4.9 Effort Mitigation

The effort increase was identified as a deployment limiting factor for a number of the target applications. Each application was then analyzed recognizing that its potential effectiveness is not uniformly distributed across all road types in a database. One method of effort mitigation is to apply applications only to the road types that would potentially provide the most safety benefit. For example, it may be reasonable to exclude Interstate Highways in the effort estimates for providing stopping locations for the Stop Sign Assistant application. Therefore some deployment savings may be realizable by considering which portion of the road network would be most applicable for those applications where cost/effort were identified as deployment constraints, while not significantly compromising the potential safety benefit of the application.

One logical way to segment the database for the purpose of evaluating applicable database scope is to define several road types, the applicability of each road type to each application, and the prevalence of that road type relative to the complete database based on road segments, which are approximately proportional to miles.

The following road classifications were derived from those commonly used for navigation database segmentation, for which database profile data is available. These definitions also prove to be useful in the segmentation of the safety application database.

- **Interstate Highways:** These are roads with very few, if any speed changes. Access to the road is controlled. These roads allow for high volume, maximum speed traffic movement between and through major metropolitan areas.
- **State Highways:** These are roads with some speed changes that allow for high volume, high-speed traffic movement. These roads are used to channel traffic to the higher throughput roads for travel between and through cities in the shortest amount of time.

- **Arterial Roads:** These roads connect roads at the next highest throughput category and provide a high volume of traffic movement, although at a lower level of mobility than the above category roads.
- **Neighborhood Connecting Roads:** These are subdivision roads, which provide for a high volume of traffic movement at moderate speeds between neighborhoods. These roads connect with higher throughput roads to collect and distribute traffic between neighborhoods.
- **Neighborhood Roads:** These are side street roads whose volume and traffic movement are below the level of any of the above throughput categories.

Table 3-16: Road type distribution metrics

Road Type	% of Database
Interstate highways and other freeways	1%
Other freeways*	2%
Arterial streets	7%
Neighborhood connecting roads	13%
Neighborhood roads	77%

* This includes state freeways and some major arteries that are not controlled access, but are necessary for efficient routing. Traffic signals will not be present in freeways but very likely will be present on non-freeway roads.

Analysis of the application and applicable road type without significantly compromising the application potential safety benefit yields:

Table 3-17: Application to road type correspondence

Application	Road Types Applicable	% of the Database
FCW	All, except neighborhood roads	23%
SSA-W and SSA-C	Neighborhood connecting and neighborhood	90%
LFA	All road types, where the speed limit is greater than 40 mph	8%
TSA	Other freeways, arterial streets, Neighborhood connecting roads	22%
CSA-C	All, except neighborhood roads	23%
CSA-W	Cost/effort was not a deployment constraint	

Effort mitigation considering road type for deployment yields the following results:

Table 3-18: Database efforts by application considering target road types

Application Type	Application	Effort Multiplier*	Optimized Multiplier*	% of Roads Deployed	Effort Considering Roads Deployed*
WhatRoad	CSA-W	1.10	-	100%	1.10
	SSA-W	1.30	-	90%	1.27
WhichLane	CSA-C	3.86	1.95**	23%	1.22
	FCW	4.10		23%	1.71
	SSA-C	-	1.30***	90%	1.27
	TSA-W	2.43	-	22%	1.31
WhereInLane	LFA-W	4.10	-	8%	1.25

*Relative to Navigation Database

**Limited to road bifurcations

***Application control mode functioning on road-level database

Deployed roads saving can only be applied to the additional effort over navigation databases. All estimates assume the presence of a navigation level database on all roads as a base. Therefore, for example, with FCW having an effort multiplier of 4.10 and being deployed on 23% of the roads, the net effort would be $1+(3.10*.23)=1.7$.

Additional insight into a composite database, taking into account the effort mitigations described above, can now be derived. A composite database effort view for each type of application yields:

Table 3-19: Composite database efforts by application considering target road types

Application Type	Application	Effort Considering Roads Deployed*	Composite Database* by Application Type	Composite Database* by Application Type
WhatRoad	CSA-W	1.1	1.4	2.3***
	SSA-W	1.3		
WhichLane	CSA-C	1.2	2.3**	
	FCW	1.7		
	SSA-C	1.3		
	TSA-W	1.3		
WhereInLane	LFA-W	1.3	1.3	

*Relative to Navigation Database

**CSA-C is a subset of FCW

***SSA-W and SSA-C use same data

Some perspective on these figures is in order. Since there are some common attributes between applications, such as geometry and curvature, the composite database estimates are not simply a summation of the individual efforts of each application.

The updated relative database creation effort, utilizing the road type mitigation above is shown in Figure 3-13. The distribution within each pie chart reflects the proportion of collection, processing, and distribution for navigation, near-term, and mid-term. Probe data was not used for the creation of the test databases and therefore was not re-estimated.

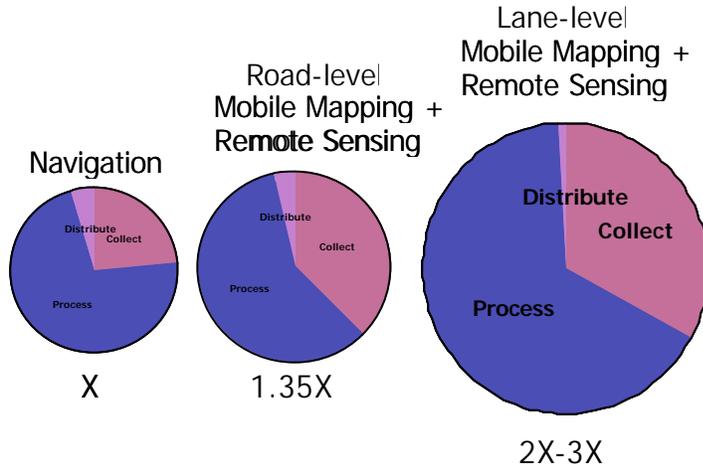


Figure 3-13: Relative database creation efforts using road type mitigation (May 2004)

3.4.10 Equipment Costs

The equipment to collect road-level databases is essentially equivalent to the equipment used today to collect navigation level databases. As noted previously, however, the cost of high accuracy collection equipment to collect lane-level data (for LFA and WhichLane applications in selected areas, such as bifurcations), for example, is between \$150K and \$200K per vehicle. It is likely that the number of high-accuracy data collection vehicles would be a limiting factor. Although this is a business issue, there would likely be a non-insignificant lead-time associated with procuring a fleet of collection vehicles of this type, even if the equipment cost could be justified. The cost and difficulties of maintaining a fleet of these high accuracy collection vehicles would also need to be considered. A reduction in the cost of this equipment is primarily dependent on a reduction in the cost of high accuracy positioning equipment.

3.4.11 Potential Rollout Scenarios

A second dimension of the deployment of enhanced databases for safety application purposes is time to deploy. Several factors affect the potential database rollout timeline, including equipment procurement, production environment creation, staffing, and direct time to collect and process.

3.4.11.1 Lead Time to Produce Databases

There are some past examples of deployment timelines that will serve as examples as we consider a practical deployment timeline for the target applications.

In Europe, the addition of speed limits was done on a country basis first, requiring approximately 12 to 18 months of calendar time to create Germany databases with speed limits. Another example is enhanced curve information in Germany, which also took approximately 12 to 18 months to deploy. Speed limits are road-level attributes and were built on top of a road-level navigation database.

It should be noted that database production deployment for areas larger than Germany, e.g., the United States, would not require a direct multiple of Germany's time to deploy. The work to create enhanced databases can be done in subdivided regions in parallel with the creation of road-level databases.

NAVTEQ is currently working to provide speed limits on controlled access roads, interstates and state highways primarily. This new data is expected to be available in the fourth quarter of 2004 and will have taken approximately one year to create. Again, these are road-level attributes.

The above examples suggest that the database creation lead time required for a database to support WhatRoad application is 1 to 2 years, partly mitigated by the potential use of a phased rollout plan, as described in the following section.

The lead time to a full lane-level database is more difficult to estimate. Using mobile mapping techniques, a lane-level database would require the driving of each lane with high accuracy equipment. Even when starting with a navigation-level database all lanes would need to be redriven. Some perspective of lead time can be gained by assessing the number of lane miles in the 5 county region in Michigan used for the EDMMap project. Lane miles was used to account for the multiple lanes required for some road type categories.

Table 3-20: Road-type categories and lane miles

	Miles of Road	Lanes/link	Lane-miles
Interstate Highways	916	2.94	2691
Other Freeways	721	2.64	1901
Arterial streets	1514	2.82	4269
Neighborhood Connecting	3179	2.49	7923
Neighborhood Roads	18949	1.96	37111
Totals	25278	2.10	53896

Roughly, there are 2.1 times as many lane miles as road miles. There are approximately 5 million road miles in a navigable database. Using the 2.1 lane multiplier, the estimated lane miles would be approximately 10 million. Assuming a collection van could cover 200 miles per day, approximately 50,000 collection days would be needed. If there were 20 high-accuracy collection vans in the fleet, operating at all times, 2500 fleet collection days would be needed. At 240 working days per year, the lead-time for collection would be over 10 years without considering any maintenance.

Reducing the lead time is dependent on getting more collection vehicles in the fleet. Increasing the fleet from 20 to 200 would theoretically reduce the lead time due to collection to 1 year. Some logistics penalty would increase this time. Another way to think of increasing the fleet from 20 to 200 is to consider that for the same investment, the equipment cost would need to decrease by a factor of 10. So, considering an Applanix equipped van at \$200K, a new cost would need to be \$20K to increase the fleet ten times with the same investment.

The Task 7 analyses identified a new classification of applications, WhichLane applications. These applications require higher accuracy than road-level databases, but lower accuracy than previously defined lane-level databases. For WhichLane applications, positioning plus map error must be below half of a lane width or around 1.5 m. Error budget needs to be favor the vehicle in order to keep costs down for high volume. Allowing the in-vehicle positioning to be <1m leads to a map accuracy requirement of <50cm. Receivers costing around \$20K with post processing of differential errors could provide a map with close to 1-meter accuracy. The <50cm \$20k receiver is currently out into the 2010 timeframe. The database to support WhichLane applications is not as equipment-cost constrained and thus, potential lead time constrained.

The creation of a production environment is also largely dependent on the creation of a production level editing environment. For road-level databases the editing environment would be very similar to the current navigation database editing environment and would not be a significant factor in the lead time for these databases. However, the lead time for a production editing tool for lane-level databases could be as long as 3 to 5 years. At least one map database supplier has done advanced work in this area that would bring this lead time into the 2 to 3 year range.

A phased approach to implementation is also feasible as described in the following section.

3.4.11.2 Potential Deployment Timeline Strategies

Certainly, the time to deploy new database enhancements is directly dependent on the resources, equipment, and personnel applied to the deployment. Reducing the volume of roads, which need to be enhanced with EDMap attributes will reduce the effort and time required for deployment. This reduction in the volume of roads to be enhanced is covered in the *Database Effort* section of this chapter.

Another approach that offers opportunities to potentially expedite the time to initial benefit is a phased rollout plan that offers some potential benefit initially and continues to increase its potential benefit as the rollout continues. A phased rollout plan has the added benefit of potentially spreading the resource burden over a period of time. The tradeoff, of course, is the absence of safety benefit in deferred areas. Therefore, the potential benefit of the phased application must be taken into account in the phased rollout plan.

Examples of potential approaches to a phased rollout are by road type, as described above, population centers, and geographic areas.

One way to phase in new maplet data is to upgrade specific types of roads initially and expand to additional road types as applicable based on the potential safety benefit of the application(s) on that type of road. The detailed analyses of application and road type are covered in the Database Effort section of this chapter.

An alternative method for a phased rollout is by population centers. This approach seeks to maximize the number of people potentially using the deployed application in the initial phases. This method of deployment opens the possibility to use data collection sources other than mobile mapping. For example, high-quality aerial imagery is more likely to be available in metro areas. Also, commercial impetus is leading the investigation of using probe vehicle data to collect traffic information. These same probe vehicles could be used for the collection of maplet relevant data. However, consideration for where an application is potentially most beneficial must be taken into account. For example, a metro-area approach may be less attractive for the Curve Speed Warning application, which is expected to be particularly potentially beneficial to safety on rural highways.

A third potential method of phased deployment is by geographic area. For example, rollout could be on a state-by-state basis. This method potentially has the advantage of being easily definable as to which areas have been enhanced and which have not.

3.4.12 Future Work

Several areas were identified as potential areas for further investigation including databases to support WhichLane applications and the increased use of probe data.

3.4.12.1 WhichLane Applications

Two distinct levels of databases were defined in Task2: road level and lane level. Road-level databases were envisioned to support applications that require knowing which road a vehicle is on, hence the term WhatRoad application. The road-level databases for EDMap were determined to be an evolution from the navigation-level databases available today. The second level of database was defined to apply maplet information, including geometry, for each lane of the road. All target applications that were not enabled with the road-level databases were defined to need the lane-level databases. The lane-level database was determined to be a revolutionary change to the database structure and processes required for navigation-level databases.

Demonstrating and analyzing the performance of the various applications revealed a very interesting potential improvement. A new application class, WhichLane, could be defined between the complexities of WhichRoad and WhereInLane. The subsequent database and positioning requirements for WhichLane applications now fall between those for WhichRoad and WhereInLane.

This opens up a number of possibilities for the map to support WhichLane applications at an effort level less than full LaneLevel as defined previously. The combined map and positioning accuracy now must fall within about one half lane width. First, it may be conceivable that lower cost collection equipment could be used for the identification of lane centers, thus reducing the equipment cost of several hundred thousand dollars for the high accuracy equipment used for the lane-level maps. In addition one could envision the possibility of driving one lane and offsetting that lane's geometry for a representation of the geometry for the additional lanes, thus reducing the number of lanes to be driven. It was also found that applications such as CSA worked quite well on road-level geometry. However, bifurcations in the road on a road-level database did not provide the CSA application with a well known future vehicle path. One could likewise envision a hybrid database with RoadLevel data in most areas and LaneLevel data only at ambiguous future path situations occur.

3.4.12.2 Probe Data

The use of probe data offers the potential for additional database creation effort mitigation.

For example, probes offers the potential to programmatically derive:

- Stopping point locations
- Traffic signals presence
- Speed limits
- Speed averages
- Number of lanes
- Direction of travel

Extracting lane information from probe data is a challenging problem. Using low cost GPS probe sensors could cause the collected data from each lane to erroneously overlap. Probe data would potentially be useful in determining lane information if the spread in the probe data were less than the lane width, making it possible to classify the lane to which each data point belongs. Having classified the data into such lane data groups, curve fitting techniques could be used to determine the geometry for each lane. However, since the spread in the data from the low accuracy probe GPS sensors exceeded the lane widths, the data could not be classified into the individual lanes, which renders a direct curve-fitting approach not feasible. As better positioning systems are offered at reduced costs the probe data could potentially be used for lane identification for the database. This lane information could then potentially be used to support WhichLane applications.

The collection of stopping locations was a major effort-contributing attribute, partly because the road type mitigations, which provided potential effort reductions for other applications, are not effective when applied to SSA. This is because SSA is potentially effective on roads that make up 90% of the database. Increased efficiencies in collection (and processing) of stopping locations by using probe data could potentially have a significant impact on the effort required to build databases to support the SSA applications.

The potential to discern speed limits from probe data was investigated. It appears that there is some consistency in the data distribution for the speeds. There are logical speed demarcations that appear with regular consistency. In the higher speed segments, the range appears to be tighter and thus have a smaller standard deviation. However, in the lower speed areas, there are larger variances possibly due to “stop-and-go” behavior from the existing “traffic noise”. This conforms to some of the preliminary assumptions about lower speed segments. It will be necessary to pursue a more thorough investigative analysis using more information to better understand these relationships.

Several key statistical metrics were calculated such as mean speed, low speed, high speed, and the number of points used in the data sample. In addition, key road metrics were separately collected; this includes the Rank, Lane Category, Speed Category, and Speed Limit attributes.

From the prototype, it is evident that the speed limit algorithm values that were calculated for each physical link do not fall within the specified parameters of the Speed Category definitions based on independently collected data. In most cases where the mean speed falls outside this range it is most likely due to the initial acceleration and deceleration of the boundaries of the segment, since each link is defined at its limits by a street marker such as a stop sign or the presence of a street light. In almost all cases where this occurs, the mean speed misses the range on the lower side because of the “stop and go” characteristics at the boundaries of the street segments. Specifically, only 46.9% of the segments met category ranges. This is not sufficient to provide a high level of confidence that using the current algorithm, without any optimizations, would provide realistic guidance about the posted speed limit.

In summary, probe data provides the potential to offer some cost mitigations. Further investigation of probe data is beyond the scope of this project and warrants further investigation.

3.5 Quality Metrics

3.5.1 Approach

An assessment of the quality of each database was developed by measuring the quality of a small, but representative, set of road segments in each database and using that subset to reflect the characteristics of the entire population of road segments. Quality analysis databases, superior in quality to the original EDMap databases, were created for each subset through the use of higher accuracy data collection equipment and/or the collection of multiple passes per segment. The quality analysis databases were then used to measure the accuracy of the mapplets in each EDMap database.

The following sections give an overview of the sampling methodology, the metrics used to measure attribute and geometric quality, and the results of the analysis. The detailed report is included in Appendix E, *Quality Assessment Report*.

3.5.2 Sampling

The accuracy and precision of the EDMap databases were determined through a sampling approach since 100% recollection of the databases was not feasible due to time and cost.

An optimal sampling size of 35 was chosen in order to minimize data collection time and cost while at the same time ensuring the sample size yields statistically significant results. This sample has been proven to yield a reasonable level of uncertainty; it makes the first digit of the proportion reliable and has been accepted as the EDMap QA assessment sample size. This number is regarded as the minimum sample needed that will yield statistically significant results. [It reduces the standard error in the binomial distribution to +/- 2-3% at a 97% confidence interval.] This sampling size dictated 35 sample routes to be driven for each subgroup, each of which contained at least 35 road sections.

3.5.3 Geometric Assessment Methodology

Relative accuracy, as opposed to absolute accuracy, was used to determine the geometric accuracy of the EDMap databases. Absolute accuracy is the spatial deviation (perpendicular distances) between the two geometries (i.e. database geometry and the ground truth geometry). Relative accuracy was calculated by first aligning the two geometries and then computing the spatial deviation between the aligned geometries. Figure 3-14 illustrates the difference between absolute accuracy and relative accuracy. In Figure 3-14A, the absolute accuracy is outside of the 10 m range, but the relative accuracy is correct. In Figure 3-14B, the absolute accuracy is within the 10 m range, but the relative accuracy is not correct.

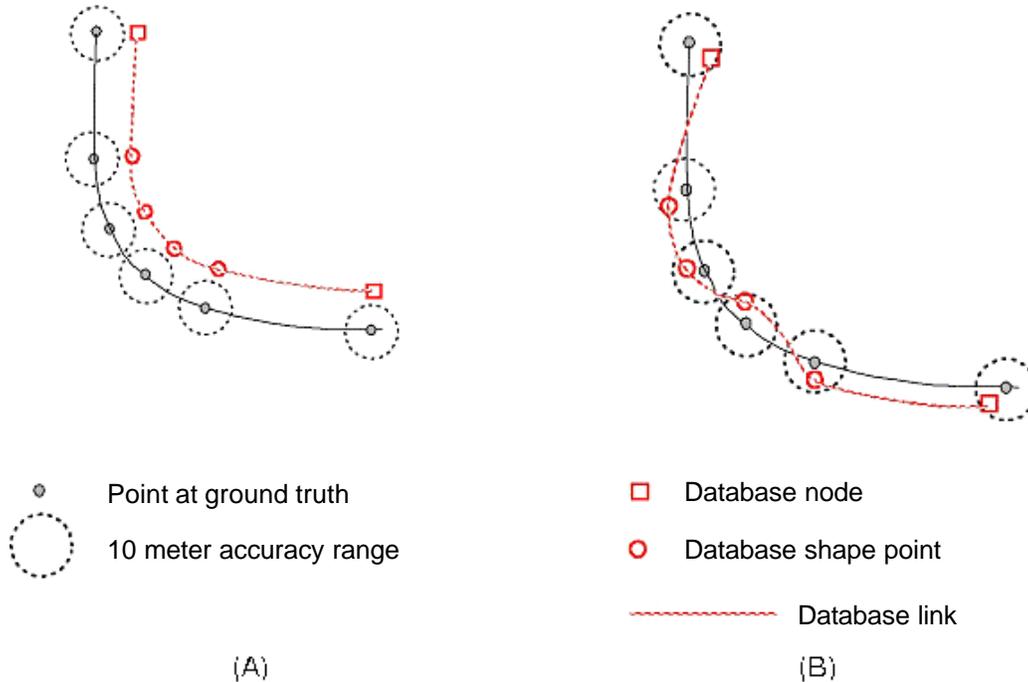


Figure 3-14: Absolute and relative accuracy

Absolute accuracy is the spatial deviation (perpendicular distances) between the two geometries (i.e. database geometry and the ground truth geometry). Relative accuracy is calculated by first aligning the two geometries, and then computing the spatial deviation between the two geometries.

A QA Geotool was designed for the quality assessment of geo databases for the EDMap project. The main task of the tool was to give a quantitative analysis of the two spline representations of the road or lane segments. The results computed by the tool were used as a measure of relative accuracy.

Consider two geometries: Ground Truth (GT) and Original (ORIG). The tool performs affine transformation to the ORIG geometry to bring it closer to the GT geometry. The QA Geotool computes relative accuracy metric using the following algorithm:

1. Find the coordinates of the center of gravity of GT spline.
2. Find the coordinates of the center of gravity of ORIG spline.
3. Translate ORIG spline so that its center of gravity coincides the center of gravity of GT.
4. Rotate ORIG geometry with respect to the GT's center of gravity by the angle calculated as the mean angle difference of the two geometries (see next section for the detailed calculation of the rotation angle).
5. Scale ORIG to GT (see next section for the details of the scaling factors calculation).
6. Determine how close the two geometries are lined up after the transformation by determining maximum deviation along the spline length.

Quantitative characteristics of the difference between two geometries include:

- Translation distances
- Rotation alignment angles
- Scaling factors, and
- Maximum deviation

Of these, maximum deviation was used as the relative accuracy metric in evaluating the quality of EDMap databases.

3.5.4 Relative Accuracy Geometry Results

Data collection for a Ground Truth database was collected for the sample set of road segments using high quality database creation techniques. Using this high quality data source, an EDMap-like database was created using the same process used for EDMap database creation. The road segments in Ground Truth database were compared with the corresponding road segments in the EDMap database. This experiment was repeated for Michigan and California databases.

The resulting relative accuracy results are summarized as follows. For the mid-term databases, approximately 86% of the geometry had maximum deviation values of less than 2 m, 80% less than 1.5 m, 70% less than 1 m, and 40% less than 30 cm. For the near-term databases, approximately 85% of the geometry had maximum deviation values of less than 2 m, 80% less than 1.5 m, and 72% less than 1 m.

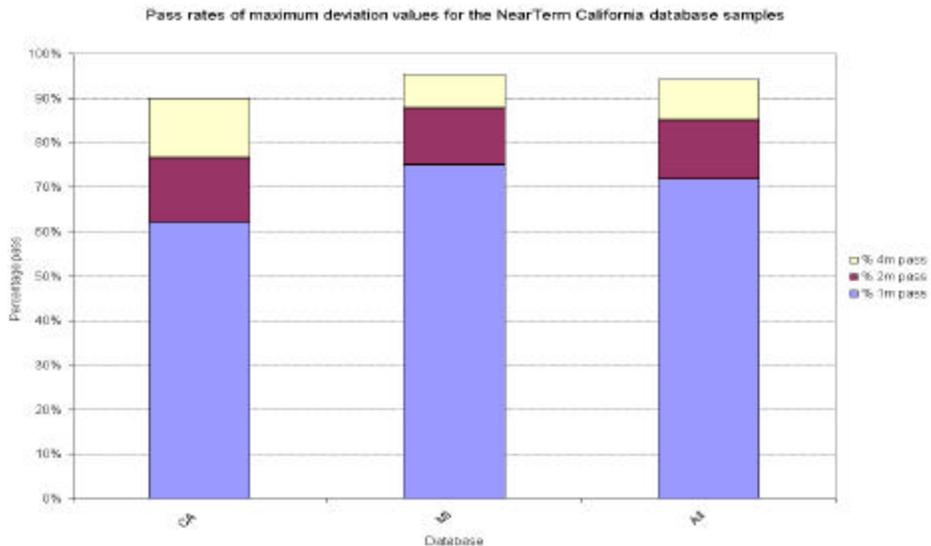


Figure 3-15: Near-term geometry pass rates

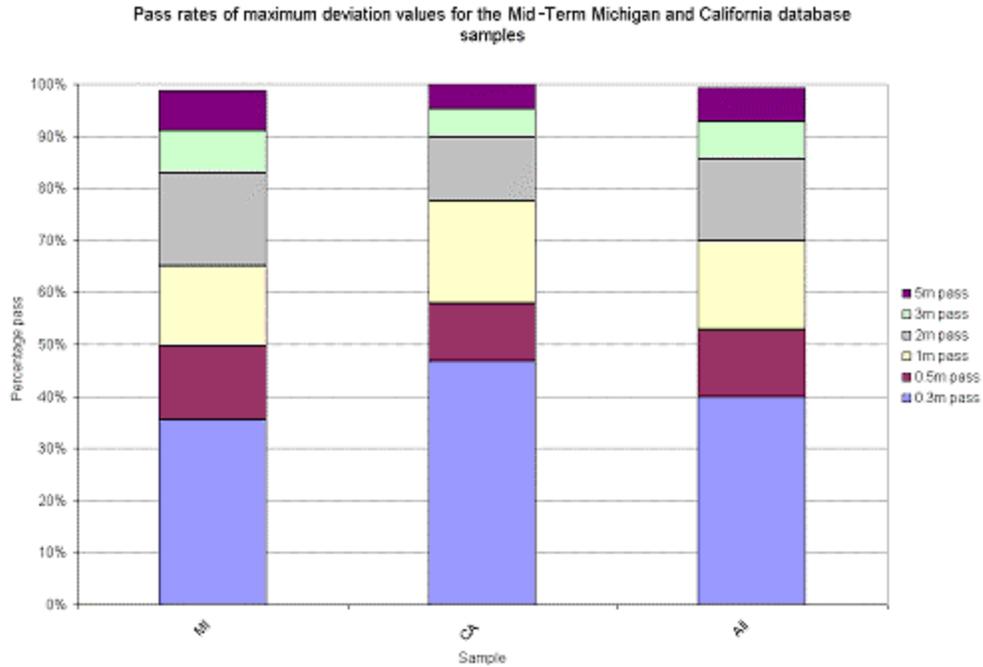


Figure 3-16: Mid-term geometry pass rates (original QA method)

The similarity of the results for the near-term and mid-term databases suggests that this relative accuracy calculation method used may not have been an appropriate measure of accuracy for a lane-level database. Further investigation of the results showed that the scale and rotation steps in the calculation may distort the geometry and thus introduce error. The following section offers an alternate alignment method that alleviates the aforementioned alignment problem.

Alternative Lane-level Metric

An alternate relative accuracy calculation method was developed that uses a different method (that avoids using tangents and scaling) to align the geometries, and thus circumvents the deficiencies of the original method. A method called Iterative Closest Point (ICP) was employed to perform the alignment step. ICP is a well known and proven mathematical method that solves the problem of optimally aligning the road geometries for relative comparison, by deriving the optimal rotation and translation parameters for alignment. Figure 3-17 illustrates the improvement of the new ICP algorithm over the original QA relative accuracy algorithm for one of the sampled database segments.

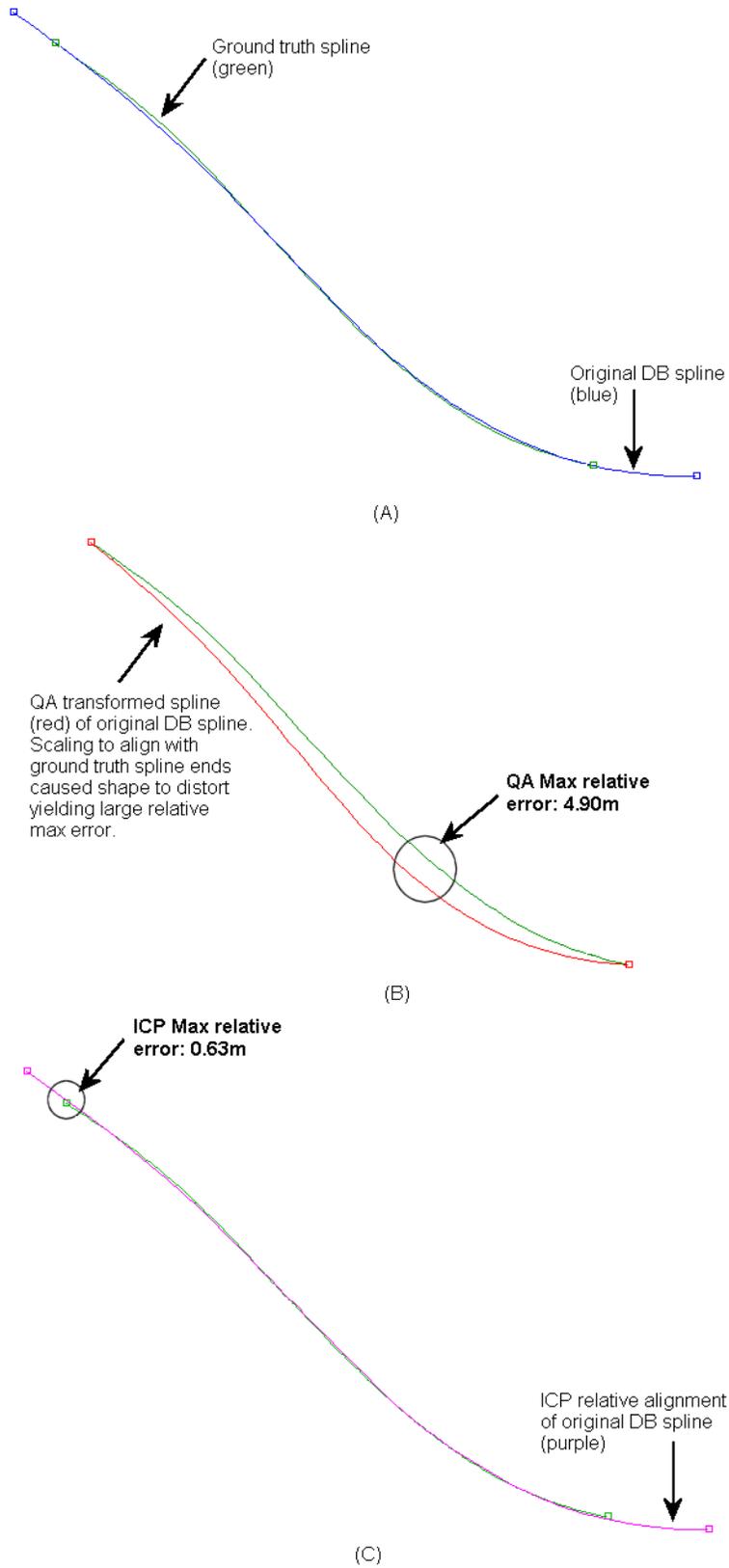


Figure 3-17: Relative accuracy result using new ICP method vs. original QA method

The resulting relative accuracy numbers using the new method are summarized as follows. For the mid-term databases, approximately 96% of the geometry had maximum deviation values of less than 2 m, 93% less than 1.5 m, 85% less than 1 m, and 51% less than 30 cm. For the near-term databases, approximately 85% of the geometry had maximum deviation values of less than 2 m, 80% less than 1.5 m, and 72% less than 1 m.

The mid-term geometry pass rates using the new relative accuracy method (ICP) are shown in Figure 3-18.

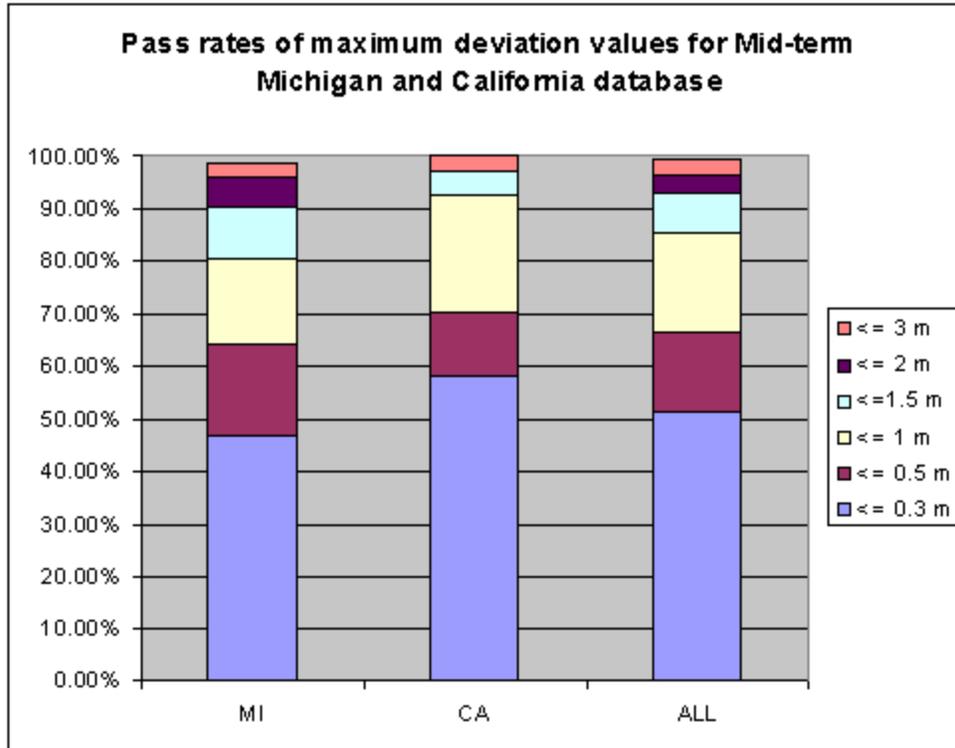


Figure 3-18: Mid-term geometry pass rates using new relative accuracy method (ICP)

3.5.5 Attribute Assessment Methodology

The attribute assessment methodology is the task of understanding the quality of the road features recorded in the databases. Attributes are the features of the road which are specifically collected for EDMap. Examples of attributes are: speed, number of lanes, and surface type for near-term, and lane width and overhead structures for mid-term.

The attribute assessment focused on four types of errors. Where appropriate, each attribute was assessed for each type of error.

Omission

An omission error occurs when an EDMap-collected attribute is present in reality but is missing from the EDMap database.

Commission

A commission error occurs when the EDMap database contains an attribute that is not found in reality.

Classification

An error in classification occurs when an attribute has been correctly included or positioned properly, however the type of the attribute (its specific information) is wrong. For example, a point attribute such as a stop-ahead sign may have been collected and recorded correctly, but incorrectly coded into the database, e.g. as a stop sign.

Position

A position error occurs when an attribute is located in wrong location on the road. The positional accuracy will be calculated using the road distance between the ground truth and the original attribute.

The attribute error analysis process utilized the following three steps:

1. **Determine number of matches and non-matches.** This will give the number of correctly identified EDMap attributes. It will also provide the number of non-matches, or errors.
2. **Determine error type.** The criteria of whether an original attribute is matched to one in reality (the QA collected data) is based on the specifications written for each attribute. For example, stop signs as a near-term attribute are to be within 1 m of the true stop sign location. A match would constitute an original EDMap stop sign falling within 1 m of the QA assessment's "ground truth".
3. **Determine degree of error.** The degree of error (the metric of positional error) is also reported. For example, the proportion of stop signs that are with 1 m, 2 m, 5 m, 10 m, etc. of reality will be given.

3.5.6 Attribute Results

The accuracy of each type of EDMap road attributes was examined and statistics were generated for link (e.g., number of lanes, speed limit, and surface type) and point attributes (e.g., stop signs, yield, signs, and stopping locations). Approximately 83% of link attributes were coded correctly and 82% of point attributes were coded correctly. For point attributes that were coded correctly, the positional accuracy of each attribute was then determined. As an example, of the stop signs that were coded correctly, 90% were placed within 10 m of the correct position, 64% within 5 m, and 10% within 1 m. The following figures summarize the results.

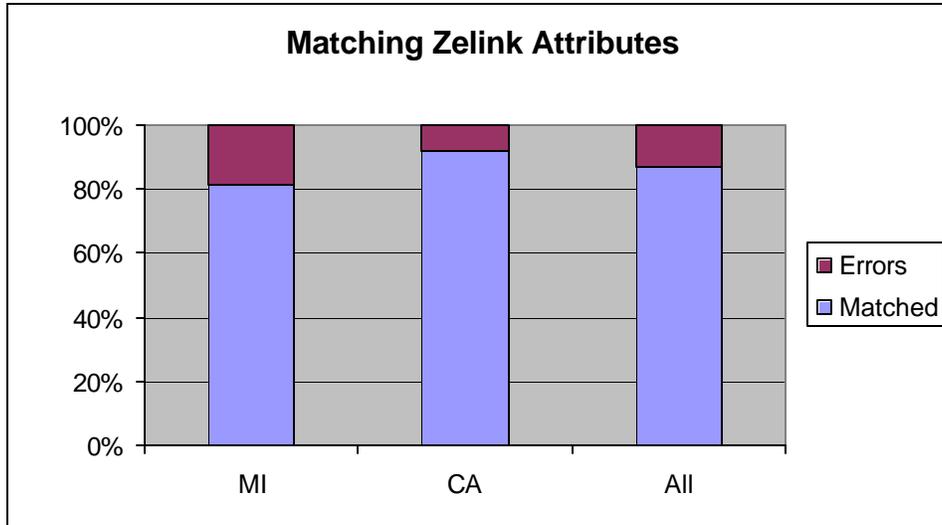


Figure 3-19: Link attributes: pass/fail by subgroup

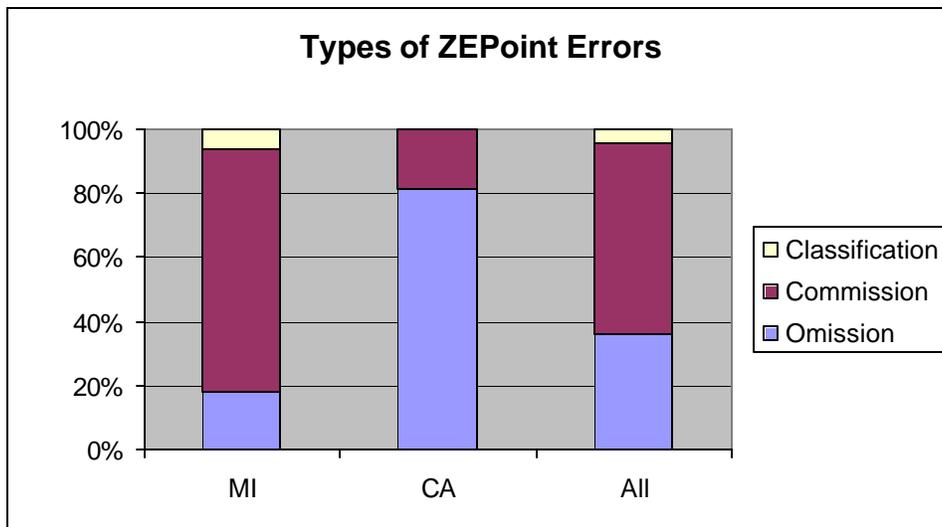


Figure 3-20: Types of point attribute errors

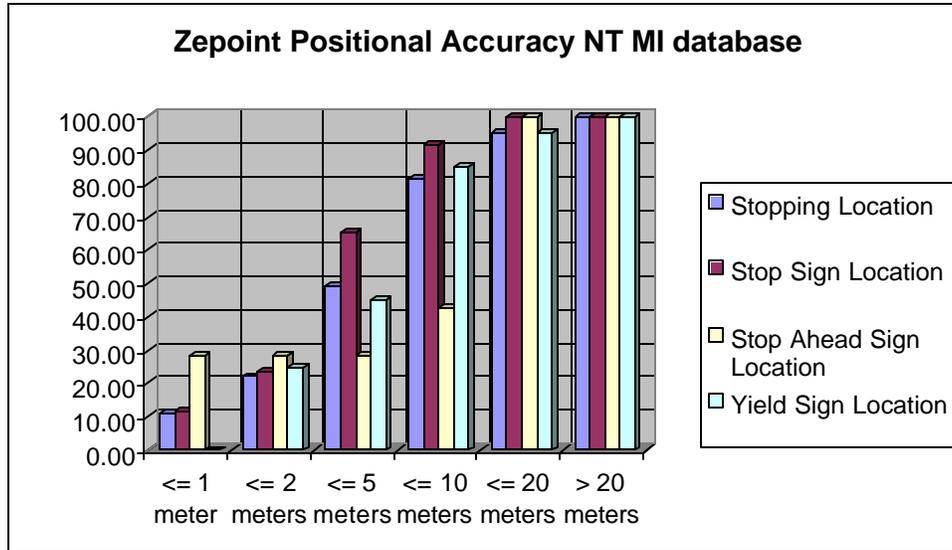


Figure 3-21: Positional accuracy of point attributes

4 Positioning Systems

4.1 Introduction

The EDMap project used two grades of positioning sensors to reflect positioning capabilities required for various safety applications identified during Task 1 of the project. Based on those findings, two levels of positioning systems were initially identified:

- Road level
- Lane level

A road-level positioning system requires an accuracy to place a vehicle on a road. On the other hand, the lane-level positioning system positions the vehicle in a lane and is also accurate enough to deliver lateral lane position, i.e. where in the lane—laterally—is the vehicle. However, during the course of the project three categories emerged, which better reflect how the applications use the positioning system.

- WHICHROAD (road level)
- WHICHLANE (lane level)
- WHEREINLANE (lane level)

WHICHROAD positioning enables the vehicle to position itself on a road and generally requires about 5 to 10 m in positioning accuracy. The initial lane-level positioning category was found to actually represent two levels of positioning requirements. For most lane-level applications it was only necessary to know which lane the vehicle is traveling in, e.g. Curve Speed Warning [Control], Forward Collision Warning, etc, hence the name WHICHLANE. This requires a positional accuracy of about 0.5 to 1.0 m and the lateral offset from the lane centerline is of no interest. The only application that required lateral lane position, i.e. WHEREINLANE positioning, was the Lane Following Assistant [Warning]. WHEREINLANE positioning, therefore, requires positional accuracy of better than 0.3 m and provides the vehicle with a lateral offset from the lane centerline.

Each OEM's vehicle was equipped with the needed positioning devices to perform the applications. Figure 4-1 shows the structure of the commonly used positioning systems in the vehicle during this project. The road-level (WHICHROAD) positioning unit grossly reflects a device available on the market today (e.g., in current navigation systems). Regular GPS position accuracy improved significantly after May 2000 when the US government discontinued the use of Selective Availability (SA). However, the road-level positioning system had the option of employing Coast Guard DGPS or NDGPS (National Differential GPS) to improve position accuracy. The corrections were obtained via a beacon receiver (CSI Wireless). See Appendix H, *Common Vehicle Components and Architecture*, for more details.

The lane-level positioning device (WHICHLANE, WHEREINLANE), however, integrates an Inertial Measurement Unit (IMU) with the GPS receiver to allow for accurate vehicle positioning under degraded GPS and DGPS signal conditions. It uses a RTK-DGPS (Real-Time Kinematic DGPS) receiver supported by DGPS base stations at each OEM test site plus one at the CAMP office. The corrections were obtained via wireless communication links (T-mobile GSM modem). See Appendix H for more details on the differential correction setup used. The lane-level positioning system also incorporated a MEMS (Micro Electro-Mechanical System) IMU. This technology was identified as having the highest potential of being mass-produced at low cost in the envisioned timeframe.

Current commercially available navigation systems are good examples for road-level positioning. They operate with current GPS components and maps to focus on vehicle navigation. These systems use map-matching algorithms to counteract coarse position accuracy and minimize lateral position ambiguity while the vehicle is on the road and in motion. This method was also employed by the EDMap road-level map system.

The lane-level map system, on the other hand, only used instantaneous measurements from the lane-level positioning system and did not utilize the map-matching algorithms. For this reason, many of the lane-level applications were not able to gracefully degrade from WHICHLANE to WHICHROAD functionalities. Whenever poor positioning would cause the vehicle to not be matched to a lane the map would report it “off road”. Once the vehicle was determined to be off road, the ADASRP (Advanced Driver Assistance System Research Platform) map access software would stop to output mapplets (CAN data messages) and the lane-level applications were forced to abruptly cease operation.

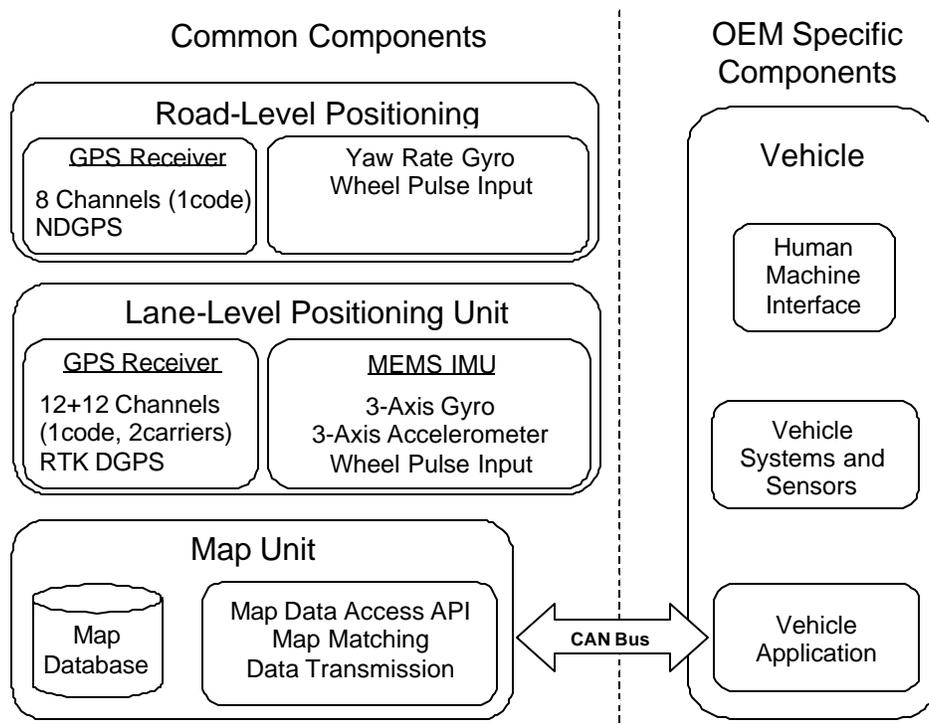


Figure 4-1: Common vehicle side positioning system structure

4.2 Road-level Vehicle Positioning

4.2.1 NTBox Positioning Device

The NTBox dead reckoning module is a hardware platform that collects and outputs sensor data that the NAVTEQ Vehicle Positioning Tool requires. For EDMap applications, the NTBox can be used in its standard configuration (SPS GPS), or it can be used in conjunction with a Coast Guard DGPS receiver, which provides the DGPS correction data. Figure 4-2 depicts the main components of the NTBox.

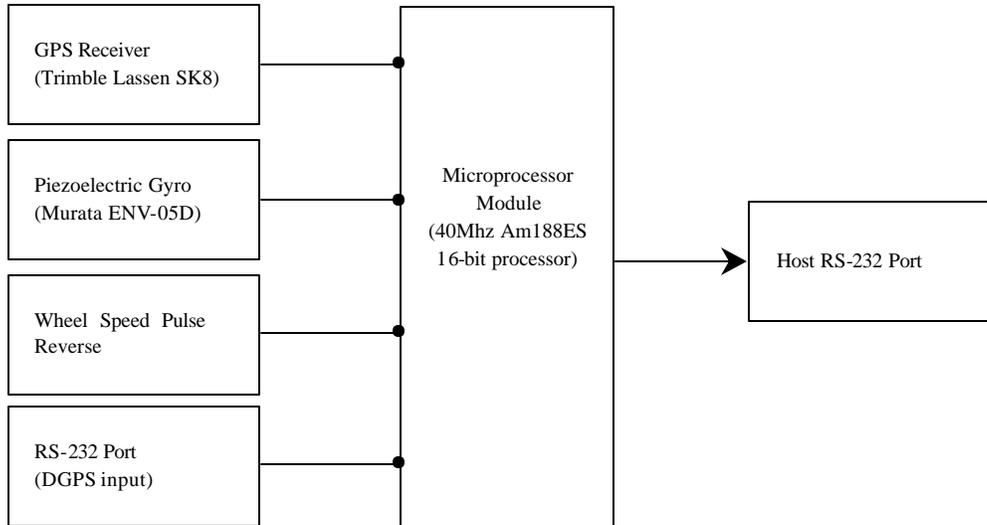


Figure 4-2: NTBox system block diagram

The NTBox was designed by NAVTEQ to represent hardware comparable to navigation systems in production today and in the road-level (for detailed specifications see Appendix H). The Trimble Lassen GPS receiver used in the NTBox is comparable in specifications to the receivers in current aftermarket navigation products. The main concern is the potential for improved accuracy using Wide Area Augmentation System (WAAS) or some other form of code based differential corrections. To cover this contingency, the NTBox was modified to allow RTCM SC-104 corrections to be input to the Trimble receiver. The NTBox also houses an inexpensive piezoelectric gyro as a yaw rate sensor.

The GPS receiver outputs the following data:

- Position, velocity, and Dilution of Precision (DOP) information once per second
- Satellite information once every three seconds
- GPS time information once every five seconds

The GPS data is received by the processing module and passed through to the host using the Trimble Standard Interface Protocol (TSIP). The processing module also samples the analog data from the gyroscope ten times per second. This data along with the accumulated speed pulse count (also taking into account if the vehicle is in reverse) are transmitted to the host in a separate TSIP packet every 100 milliseconds. Figure 4-3 shows the front panel of the NTBox used for the EDMap project.



Figure 4-3: NTBox road-level GPS receiver

4.2.2 Road-Level Positioning Performance

Overall, the road-level positioning device operated satisfactorily (see Figure 4-4). Due to the use of map matching the system performance was very good and maintained the vehicle position on the road.

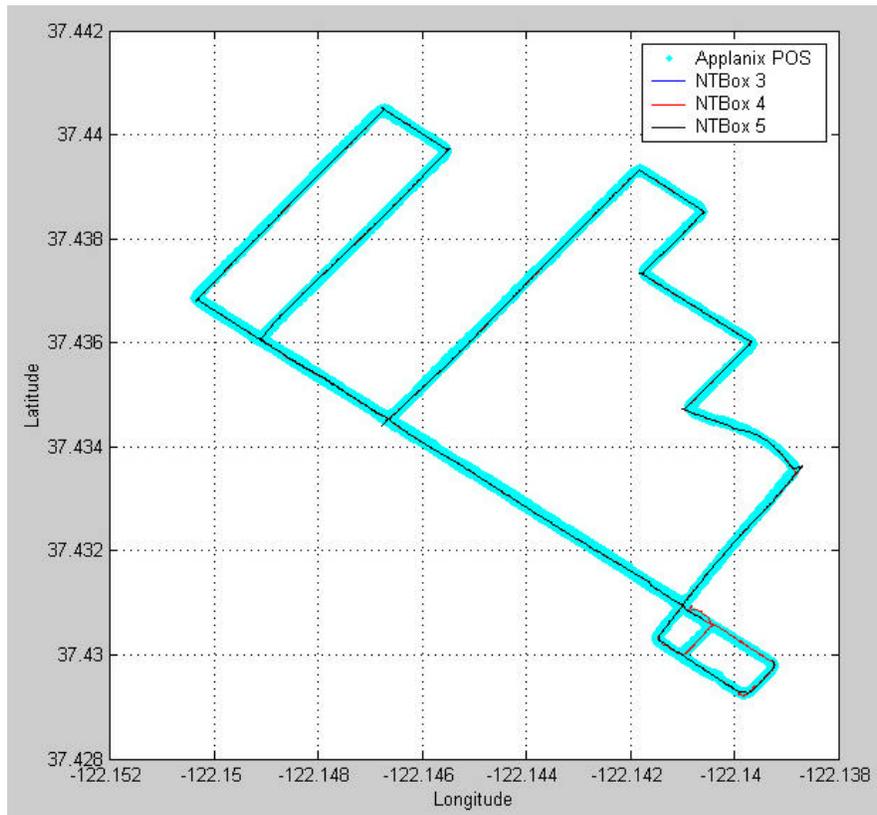


Figure 4-4: Road-level positioning performance on the Toyota Palo Alto demonstration route

Three driven NTBox vehicle trace match well to the output of a highly accurate Applanix Corporation Position and Orientation System (POS) shown in white (see Appendix H for more information on capabilities of available Applanix POS systems).

In order to further improve position accuracy, a Coast Guard DGPS (National DGPS: NDGPS) beacon receiver (CSI Wireless MBX-3) was used for road-level applications. To better quantify the improvement in position accuracy, data was collected while the vehicle was stationary. The DGPS signal line was connected and disconnected in 5-minute intervals to determine what difference in accuracy the DGPS receiver made. The DGPS operational status was checked by monitoring DGPS fix mode with the ADASRP. The DGPS mode changed from 2 to 3 in 30 sec, when the DGPS receiver starts operating in DGPS Fixed mode. As can be seen from Figure 4-5 below, there was no significant improvement in positioning accuracy when compared to using the road-level position sensor by itself.

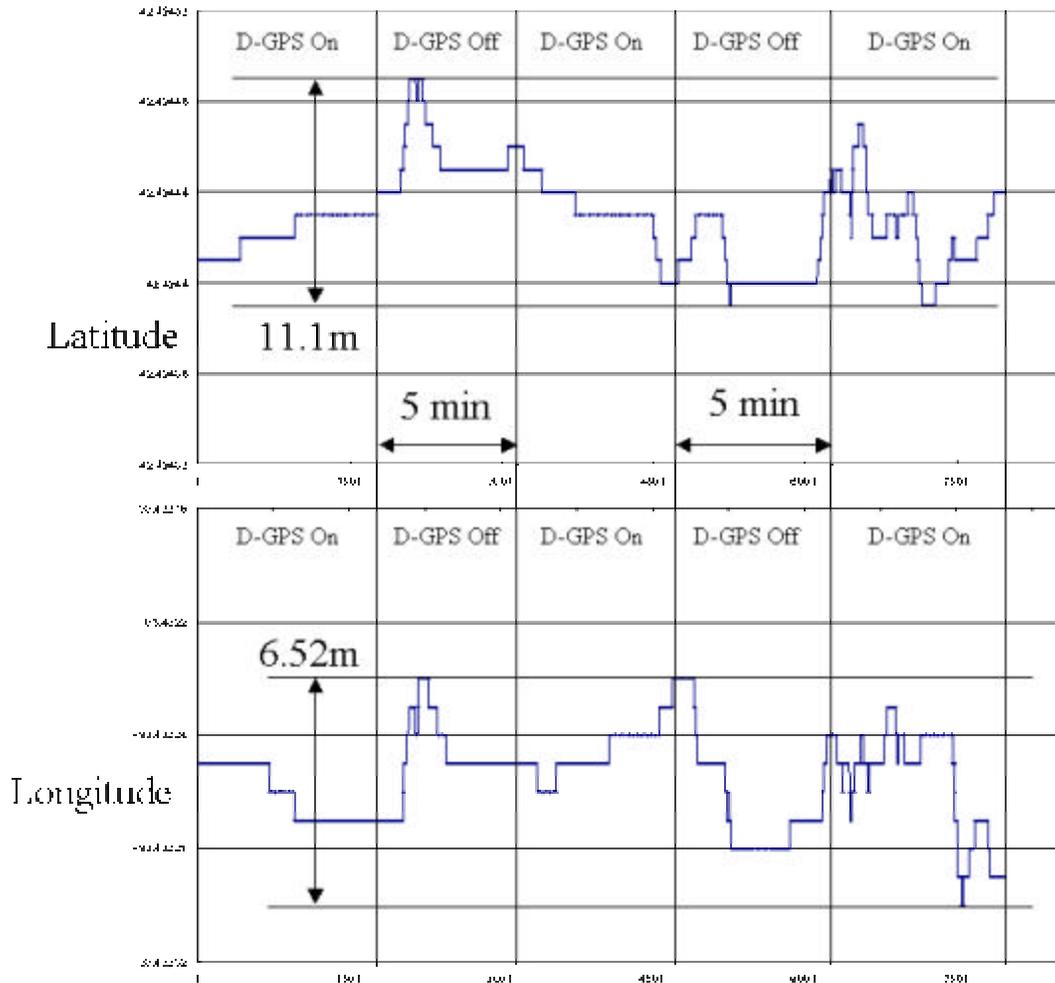


Figure 4-5: Coast Guard DGPS correction (on/off) – Station ID 46 SNR34 used during this test

Therefore, the applications were deemed feasible and were demonstrated without any differential corrections enabled.

4.3 Lane-level Vehicle Positioning

4.3.1 Honeywell Prototype Automotive Positioning Sensor (PAPS) Positioning Device

Whereas the NTBox represents what is commercially available for vehicle positioning today and in the road-level, the lane-level applications require a degree of accuracy that the NTBox is not capable of providing. The Honeywell PAPS DGPS receiver is the source of GPS vehicle positioning data for all lane-level applications. The PAPS unit provides the following position accuracy needed for lane-level applications. Figure 4-6 shows the positioning sensor installed in all the EDMap test vehicles.



Figure 4-6: Honeywell PAPS positioning sensor

Table 4-1 shows the position accuracy of this positioning device and Table 4-2 gives a more detailed description of the PAPS unit components.

Table 4-1: PAPS positioning accuracy during GPS outages of up to 10 sec duration
(as claimed by Honeywell)

Solution Type	GPS Autonomous Performance (1s)	INS Performance Between Epochs (1s)	INS Performance During Outages Straight Trajectory (1s)	INS Performance During Outages Curved Trajectory (1s)
Single point or Autonomous GPS	20 m	2 m	5 m	10 m
Pseudorange Differential	1 m	30 cm	1 m	2 m
RTK – Floating Ambiguity	25 – 100 cm	30 cm	1 m	2 m
RTK – Ambiguity Converged	2 – 20 cm	10 cm	30 cm	60 cm

The project identified the potential of a MEMS based IMU and integrated DGPS receiver to be able to penetrate the automotive market to provide lane-level positioning. The EDMap team selected the Honeywell prototype INS as a way to evaluate the positioning potential and to motivate continued development of automotive grade high accuracy INS. This PAPS unit is comprised of the following features:

Table 4-2: PAPS description

Feature	Description
GPS Receiver	A dual frequency (L1, L2) 24 Channel (12 channels each) DGPS Receiver with carrier phase differential capabilities.
GPS Antenna	A multi-path rejecting GPS antenna.
Inertial Measurement	A MEMS inertial measuring unit (IMU) consisting of angular rate measurement gyros and accelerometers configured to allow measurement of rate and acceleration respectively in all three dimensions of space.
Wheel Sensor Integration	The means to accept vehicle wheel speed data in a serial format.
Integrated INS/GPS Solution	Provides a solution that takes advantage of the fast update rates of the independent inertial solution and the high accuracy of the GPS solution in an optimally integrated INS/GPS solution.
Data Recorder	A commercially available compact flash card data recorder stores output data messages for further analysis.

A number of base stations located at each participating OEM location and CAMP provided carrier phase differential GPS corrections data (RTCA messages) for use with the PAPS unit during application development and testing. The PAPS unit receives this data through a RS-232 serial input bus via a Global System for Mobil communications (GSM) modem. The PAPS unit is also configured to receive wheel speed data through an RS-232 serial input bus. Details about the DGPS setup used for EDMap testing can be found in Appendix H. Each OEM was responsible for providing wheel sensor data in the proper format and the approaches varied for each OEM. The PAPS unit provides high precision position data updated at 50Hz and detailed status information at 1Hz through a standard RS-232 serial output.

4.3.2 Lane-Level Positioning Performance

Overall, the Honeywell PAPS unit performed well for WHICHLANE applications and failed to deliver robust positioning to WHEREINLANE applications. Under the scenarios tested, the unit usually placed the vehicle in the correct lane. However, under certain GPS outage conditions the sensor performed poorly and lane matching could not be maintained. These conditions include:

- Long GPS outages under a series of overpasses
- Heavy tree cover over the road (especially in California test area)

Under these outage conditions (larger than 10s) the Honeywell PAPS unit did not perform as well as originally anticipated resulting in robust WHEREINLANE positioning being moved into the long-term. A contributing factor was the at times unreliable DGPS communication link (T-mobile GSM wireless network). The teams experience is that the cell phone network was a good way to distribute differential corrections for the test and evaluation of the EDMap applications. However, it does not represent a deployable solution.

Possible transmission methods include:

- Satellite-based transmission (currently available for a fee)
- Ground based digital radio

The Honeywell PAPS DGPS receiver was planned to employ a wheel speed signal input to improve positioning and initialization performance. Only Ford succeeded to feed the wheel speed signal to the PAPS unit. Based on their experience, wheel speed information greatly improved the initialization and alignment procedure of the unit when powering it up. Wheel speed input also allowed the PAPS unit to more reliably eliminate gyro drift, e.g. when wheel speed indicates that the vehicle is stopped the drift can be easily compensated for.

The overall performance experiences of the Honeywell PAPS unit are summarized next using data collected during the Ford demonstration drives on March 24-26, 2004. The demonstration drives were conducted in a freeway environment, hence, we experienced several GPS outages due to structures over and along the road, e.g. overpasses.

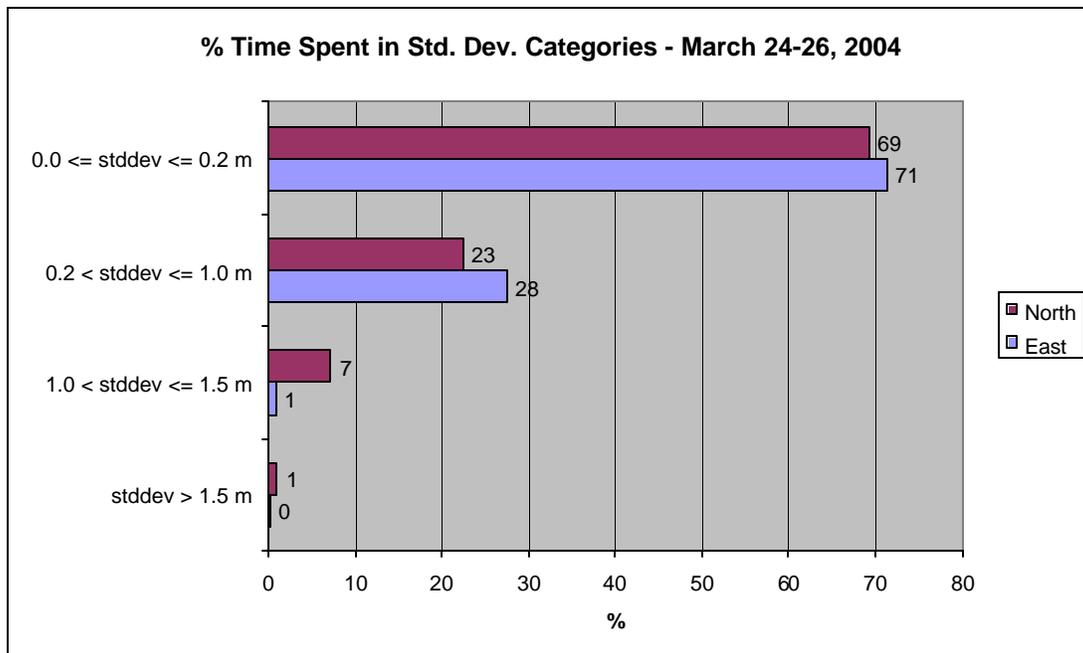


Figure 4-7: % time spent in standard deviation categories – March 24-26, 2004

Figure 4-7 summarizes the positioning performance encountered on the drives. The performance is divided into four categories:

- WHEREINLANE-level: $0 \leq e \leq 0.2$ m (assumes 0.3 m map error)
- WHICHLANE-level: $0.2 < e \leq 1.0$ m (assumes 0.5 m map error)
- WHICHLANE-level: $1.0 < e < 1.5$ m (assumes 0.3 m map error)
- WHICHROAD-level: $e \geq 1.5$ m (map error not relevant)

The Honeywell PAPS unit itself reports these standard deviation values. There is one for each axis—east and north. The chart above represents the performance over 14 demonstration drives on different days and at different times of the day that lasted a total of 3.8 hours. It includes the challenges of overhead bridges blocking satellite signals and interrupted DGPS corrections.

The following figure represents the best run (in terms of Honeywell PAPS self-reported standard deviation) on one of Ford's March demonstration drives. Overall, the experiences that DaimlerChrysler had during their test and demonstration drives confirms the result presented here.

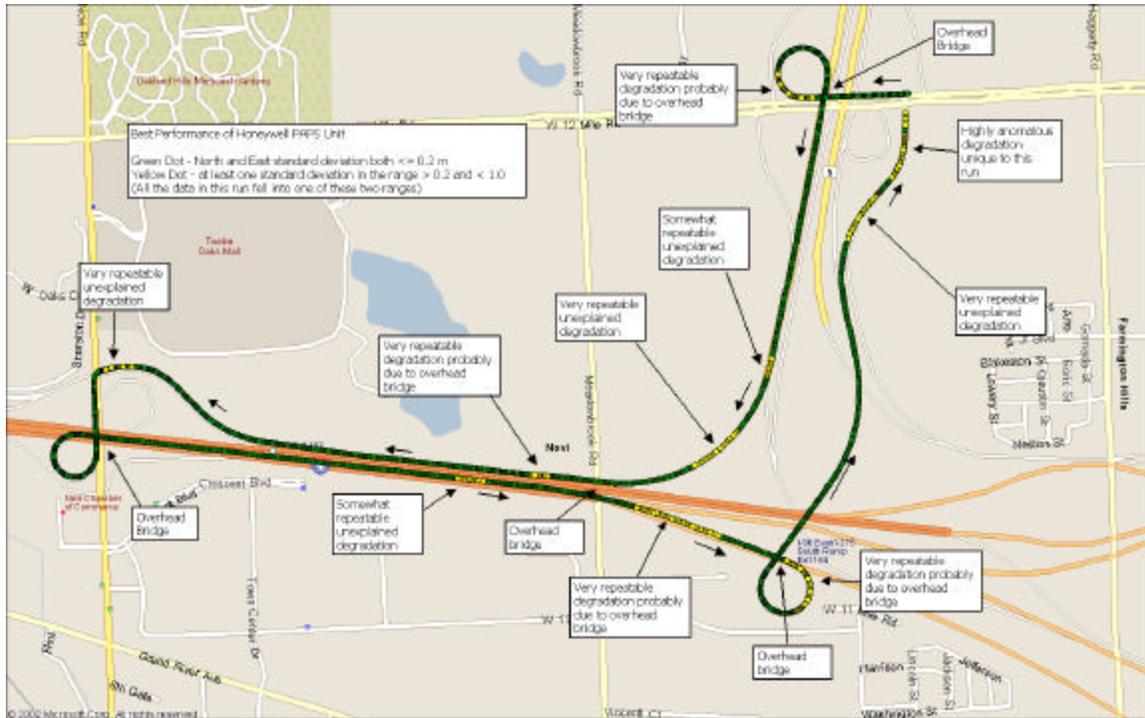


Figure 4-8: Best run of March demonstration drives

In Figure 4-8 the demo route is shown in green and yellow dots. The green represents positions where the standard deviation of both the north and east components is less than or equal to 0.2 m. The yellow represents positions where at least one of the components was in the range greater than 0.2 m and less than or equal to 1.0 m. In this run, there were no positions that were outside these two ranges.

One pass through this route goes through five underpasses (four bridges—one passed under twice). As can be seen, in four of the five underpasses, the standard deviation goes to yellow. This is better-than-average performance compared to the other runs collected. It is not unusual to go to yellow after each underpass and occasionally stray into the greater than 1.0 m range. At all times during this drive, lane matching was maintained.

Also in Figure 4-8 there are yellow sections with no apparent reason for the increased error probability. An on the road review revealed the sections are downstream of overhead traffic signs. The ones marked "very repeatable" occur in nearly all (if not all) of the runs collected. The ones marked "somewhat repeatable" occur in half or less than half of the runs.

Since many team members commented on the GPS outage behavior of the PAPS unit we will discuss them here in some more detail. Overall, the following reasons were identified as primary causes for GPS outages and, therefore, unreliable PAPS positioning:

- Frequent GPS satellite outages, due to trees, bridges, and even large overhead road signs (see Figure 4-9, Figure 4-10, and Figure 4-11)
- Large reacquisition times of lost satellites
- Higher than expected position drift during a total satellite outage (up to 30 seconds), e.g., driving under an overpass, tunnel
- Unreliable DGPS coverage, at times



Figure 4-9: Typical overpass that causes total satellite outage and results in high GPS errors

Another reason for deteriorating GPS accuracy is the relatively harsh environment, prone to GPS outages, of a vehicle traveling down a road. Many times the GPS receiver would not have enough time to recover from a GPS satellite outage before encountering a second one, extending the time of low position accuracy significantly.



Figure 4-10: Overhead road sign that would lead to a partial satellite blockage

The DGPS coverage is at times unreliable mostly due to the use of a regular cell phone modem to connect to the differential base station. The dial program usually automatically detects a loss of correction information. However, a loss of about 60 to 90 seconds of DGPS information has to be expected during a modem redial, which combined with a satellite outage due to driving under a bridge, quickly causes the GPS position accuracy to drop below acceptable levels.



Figure 4-11: Heavy tree cover on residential streets blocks satellite signals

Situations where heavy tree cover prevented the GPS receiver from receiving adequate GPS satellite information presented the most challenging environment to the Honeywell PAPS unit. Toyota Technical Center encountered such conditions particularly on their California demonstration route. The Stop Sign Assistant, at times, performed poorly due to low position accuracy. Figure 4-12 shows an example of an extreme drift of the positioning unit on the TTC demonstration route, which went through a residential neighborhood with extremely heavy tree cover.

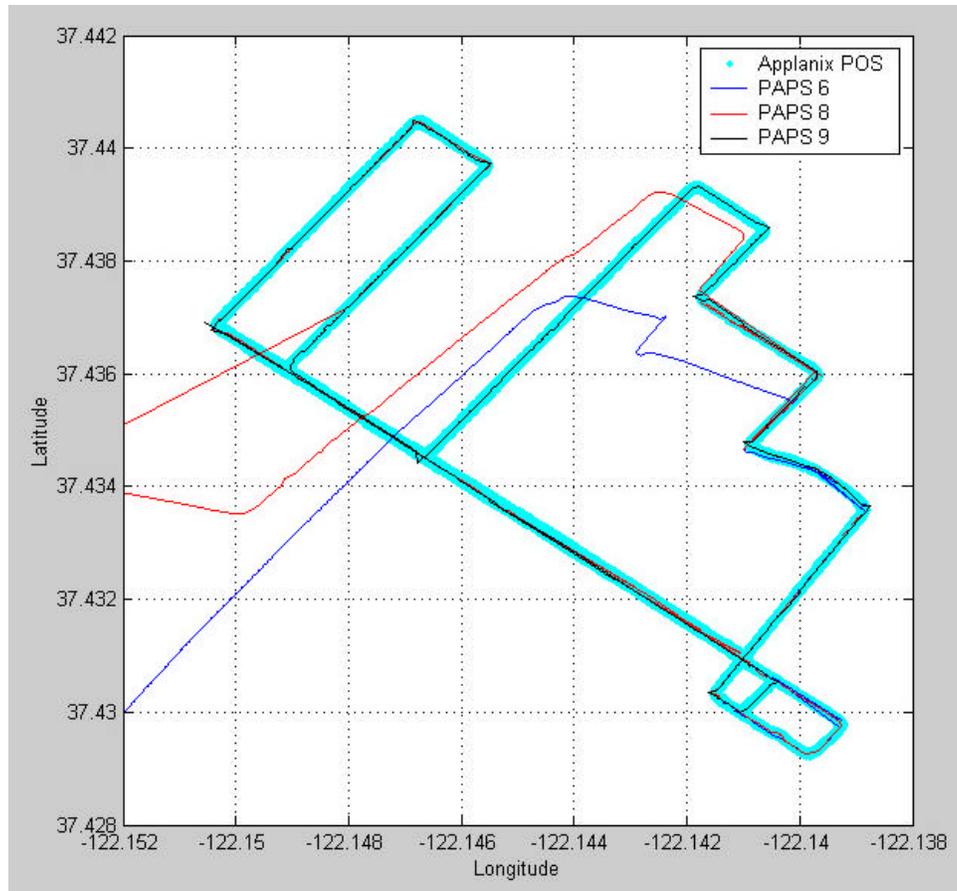


Figure 4-12: Lane-level position system drifts under adverse conditions

Figure 4-12 shows the PAPS performance on three drives along the route at different times of the day. Since the tree cover is the same on each of the drives, the impact of the satellite constellation, which changed over the course of the experiment, can be clearly seen. The first drive (blue line) represented the worst conditions at times of low number of satellite over the test area. The positioning device is unable to maintain a reasonable positioning error. Conditions improved (more satellites are over the test area) and the second drive (red line) shows a slightly better positioning behavior. On the third drive, a good number of satellites were visible over the test area and the positioning device performed reasonably well. It should be noted, that the wheel speed sensor was not connected to the PAPS unit during these tests and that wheel speed input might have improved the outage and recovery behavior on drives one and two.

4.4 Future Positioning System Improvements

Future positioning capabilities will depend on a variety of issues. Generally, the positioning capability and accuracy will mostly depend on the Global Navigation Satellite System (GNSS) capabilities and constellation. In the road environment, however, navigation satellites will be blocked at times and a dead-reckoning device (also referred to as Inertial Measurement Unit (IMU)) is needed to cover those outages. Hence, two components need to be investigated:

- Satellite constellation improvements (availability and accuracy)
- IMU developments and improvements

This section will briefly investigate the current predictions and alternatives.

4.4.1 GNSS Developments

Current developments regarding navigation satellites will improve the accuracy of positioning devices significantly in the future. Current GPS receivers are, after the selective availability (SA) was turned off, capable of delivering WHICHROAD positioning well. Long outage and urban canyon scenarios still present challenges, but overall the achievable positional accuracy is acceptable. Figure 4-13 shows how the positional accuracy will develop over time. The upper bar (labeled GPS 1f – ) represents today's single frequency GPS receivers, which are capable to deliver between 5 and 10 meters accuracy. With Galileo being operational around 2010, a single frequency Galileo receiver will deliver approximately the same accuracy, however, a combined GPS and Galileo receiver can make use of the increased number of satellites provided by both systems (about double the number of today's at any given time) and make the standalone positioning significantly more robust by increasing the DOP (dilution of position) and reducing some of the outages caused by partial blockage of the sky.

On the other end of the spectrum, WHEREINLANE positioning, which requires positioning better than 30 cm (bottom bar in Figure 4-13 – ) accuracy will also not change significantly, however, with the introduction of Galileo the robustness of these receivers will greatly improve. Dual frequency receivers will allow rapid satellite reacquisition after outages and the larger number of total satellites will greatly increase the availability of the system. Currently, civilian dual frequency GPS capability is expected after 2013 and Galileo is currently planning to deliver the second and third frequency on a subscription basis. It should also be noted, that these receivers will require carrier-phase differential correction information in order to deliver the highly precise RTK (real-time kinematics) solution. These correction information would have to be widely available in order for a successful deployment to occur.

An area attracting increased attention is the WHICHLANE positioning accuracy represented in the center of Figure 4-13, roughly spanning the range of 0.5 to 1.0 m of positioning accuracy. There are currently two technologies available to get positioning close to and in this range. The first are single frequency DGPS receivers, which generally deliver an accuracy of 1 to 3m (labeled as ) using, for example, WAAS (Wide Area Augmentation System) for correction information. Narrow correlator DGPS receivers (labeled as 1f DGPS – ) can push this accuracy into range required to perform WHICHLANE applications today. Dual or triple frequency Galileo narrow correlator receivers would be able to achieve WHICHLANE positioning without differential corrections after the system is operational in 2010, using a second or third frequency to compensate for errors introduced due to interferences of the ionosphere on the satellite signal (labeled 1f/2f Galileo – ). This situation would improve and be more robust, after GPS satellites deliver a second civilian code on the L2 estimated to occur after 2013 and again after the introduction of a third GPS frequency around 2017 (labeled 2f/3f GPS – )

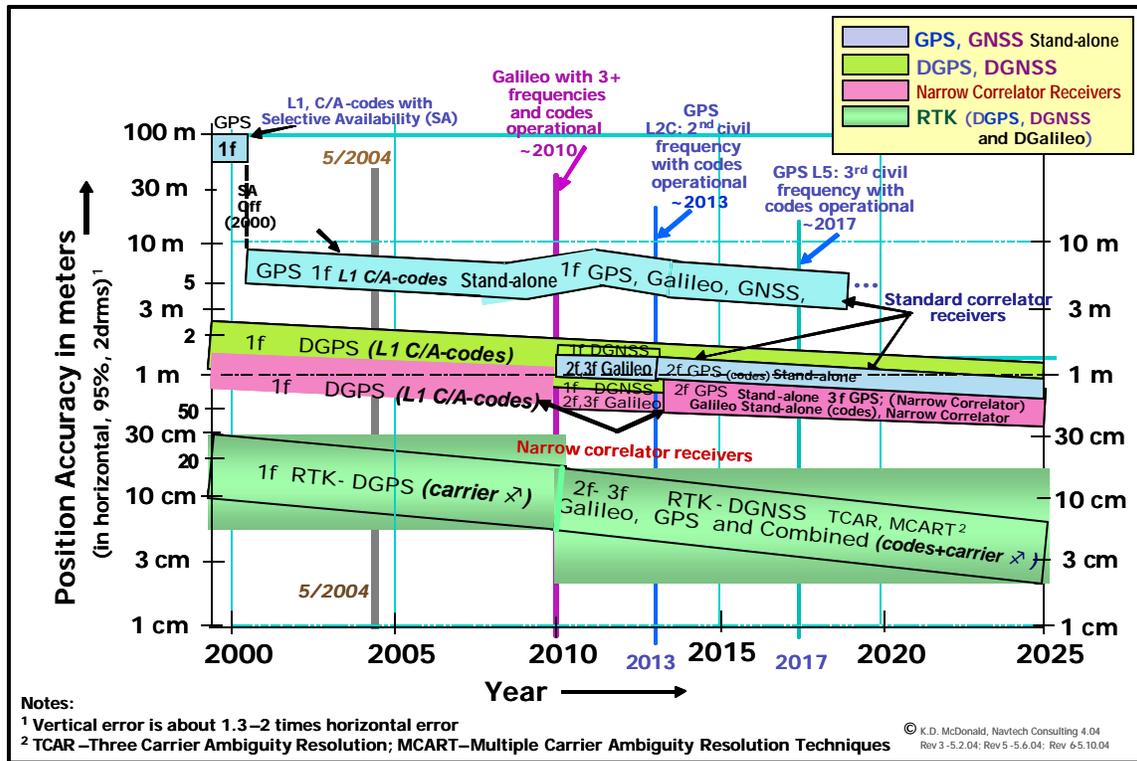


Figure 4-13: Accuracy Capabilities by Year for Various GNSS Operating Modes

Currently, narrow correlator receivers are expensive (between \$2000-\$5000). According to Novatel, there is no fundamental restraint on narrow correlator receiver prices. As volume increases price will decrease. It is estimated that narrow correlator receivers can be available at automotive quantities (+100k units) for under \$100 with a lead-time of up to 2 years to ramp up production.

It should be noted, that much of the timeline presented here greatly depends on the satellite system implementations and upgrades. For example, current GPS satellites last longer than originally anticipated, postponing the replacement of those older satellites with newer, more capable ones. The timeline presented already takes estimated delays into account, although further delays are possible.

4.4.2 IMU Developments

Whereas the GNSS constellation and capabilities determine the achievable position accuracy based on a variety of configurations, a dead-reckoning device is needed to cover satellite outage conditions. The quality of the IMU, i.e. drift of the gyros in the unit, will directly impact the positioning accuracy during a satellite outage and the outage duration that can be accommodated by the positioning system. Figure 4-14 shows the capabilities of several classes of IMUs and how their quality will impact position error. The plot assumes that the IMU was initialized well before the outage occurred. Note the logarithmic scale on the Y-axis. The gyro drift error increases over time. As can be seen, a 10 deg/hour IMU can deliver WHICHLANE positioning (0.5-1.0 m positioning error) for about 30 seconds. In contrast, a 1 deg/hour IMU will be able to deliver this accuracy up to 60 seconds. A highly accurate 0.1 deg/hour drift IMU, which is not believed to be widely available for vehicle deployment, could maintain a low GPS error for much longer.

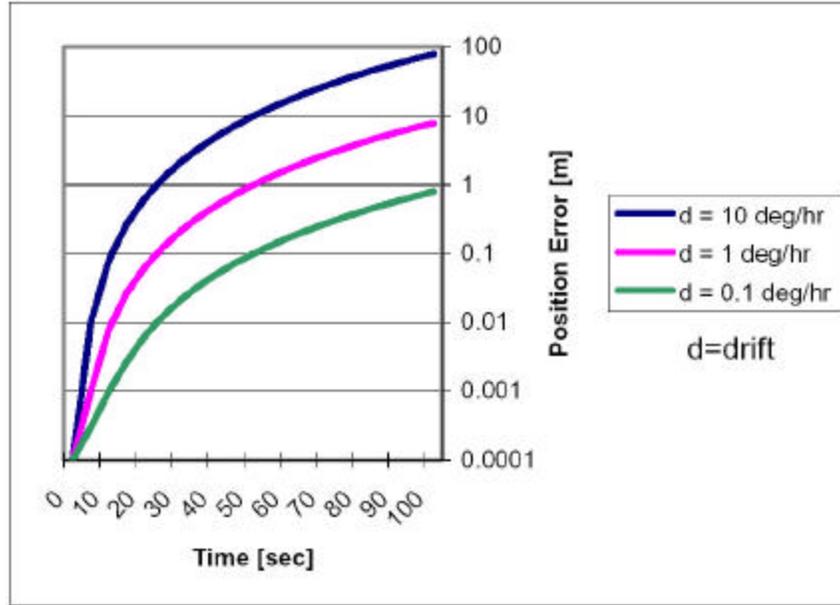


Figure 4-14: Free inertial drift of three IMU classes (gyro only)

(Source: EDMap Task 8b report page 79)

Currently, there are a variety of gyro technologies on the market and incorporated in IMUs. The following list summarizes the available options:

- Mechanical gyros
- Fiber-optic gyros
- Ring laser gyros
- Micro Electro-Mechanical System (MEMS) gyros

Currently none of these options is cost effective with regards to automotive requirements. Out of these options, only MEMS gyros (more details on MEMS technology can be found in Appendix H) have shown potential to be viable for automotive quantity production at cost reasonable for vehicle integration. MEMS gyros are based on silicon and their price is mainly depended on the production volume. This was the principal reason as to why the EDMap project participants decided to evaluate a MEMS prototype unit during the application test and demonstration.

It is currently expected, although this timeline is highly speculative, that a 10 deg/hour MEMS IMU similar to the one tested during this project would be available to the automotive sector starting at 2005. On the other hand, a 1 deg/hour MEMS IMU is expected to enter the market between 2006 and 2010.

On a final note it should be mentioned that currently most IMUs fall under the International Trade of Arms Regulation (ITAR). In order to deploy a 1 deg/hour IMU in a consumer vehicle, changes and/or exceptions to these regulations need to be considered. In talks, Honeywell also indicated that it is unlikely that export ITAR regulations will be eased on an IMU of less than 1deg/hour. Hence, vehicle application will be limited to 1 deg/hour IMU performance in the future.

5 Summary and Conclusions

5.1 Introduction

EDMap project tasks were designed to focus on safety related applications, and to use the application requirements to drive improvements needed in the map database. From this perspective, the EDMap project can be viewed in two distinct phases: a “paper” phase and a “practice” phase.

The paper phase was a research and planning phase conducted to determine application and map requirements based primarily on analysis and past experience. This paper phase established the initial conditions for the practice phase where map and application requirements were put into practice. The implementation evaluations in many respects confirmed the initial requirements. In several key areas, however, the practice phase helped stratify and prioritize the must-have and optional requirements. This selection process came about as the result of careful development iterations of both the map database as well as the applications themselves.

With that in mind, the EDMap project summary is captured by the following points:

- Application and maplet evaluations led to key optimizations
- Vehicle positioning capability is in the critical path for deployment
- The demonstrated EDMap applications provide a good basis for a roadmap of map enabled safety applications

Each point is summarized below.

5.2 Maplet Optimization

The EDMap paper phase produced a map effort estimate that, especially for the lane-level map, projected effort multipliers significantly beyond feasible limits (5 to 7 times that of the current navigation intent map database). However, review of the maplets with respect to content and extent has shown potential for significant effort reduction compared to estimates made earlier in EDMap.

Map content optimizations were achieved through a variety of means, and the result was that maplets were culled from the original requirements list and map creation effort was reduced. Map extent optimizations were also made toward the end of the evaluation process. Each application developer reviewed the respective accident exposure, and determined the effect on potential application safety benefits if road coverage was reduced. For applications needing residential streets, the map extent effect on optimization was minimal due to the high percentage of residential roads in the United States. For applications not needing residential streets, the effect was quite significant.

Figure 5-1 shows the effect of maplet optimization on the original 5 to 7 effort multiplier. For maplets to support all applications, the effort multiplier was reduced to approximately 2 to 3. This was an important result that provided increased potential of advanced maps to aid safety applications. The maplet optimization effects on a per application basis, also shown in Figure 5-1, points toward potential map database migration paths.

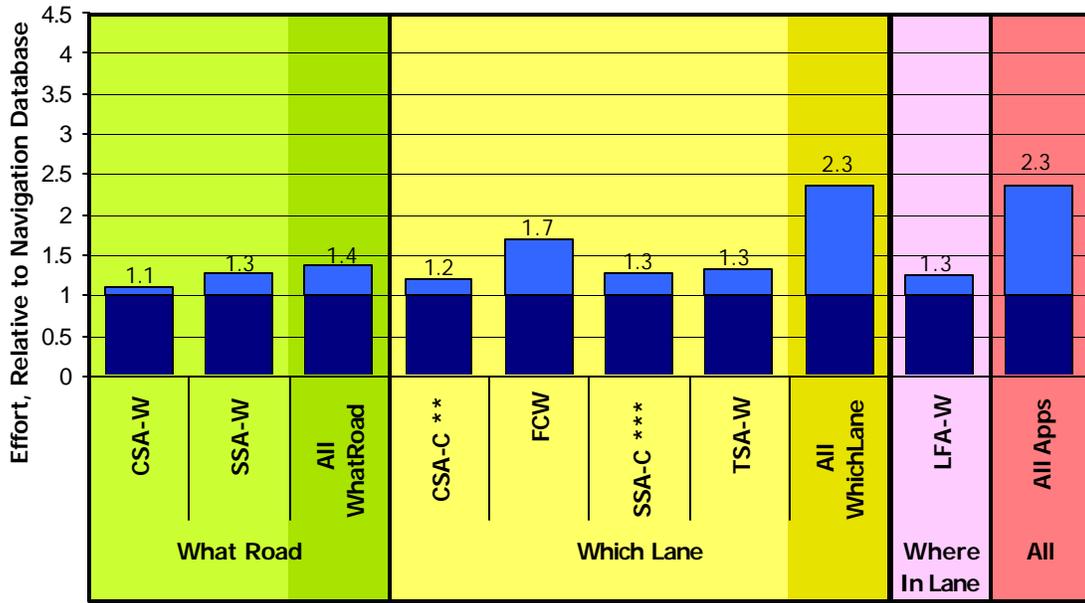


Figure 5-1: Results of mapplet optimization with regard to content and extent

5.3 Vehicle Positioning

At the beginning of EDMap, the prevailing view on vehicle positioning capability was that vehicle positioning was adequately addressed by either existing or planned GPS capability or improvements. As the project progressed, the view was partially confirmed for the near-term (road-level) applications, where the road-level map effort multipliers were very manageable, and the accuracy and reliability of production grade vehicle positioning sensors (navigation level GPS and dead reckoning sensors) in conjunction with map matching proved to be acceptable in application evaluations.

The view for high accuracy positioning, capable of determining lateral offset in a lane for Lane Departure Warning, became more pessimistic during the project. The positioning system did not maintain reliable lane offset information due to reasons described in Chapter 4, *Positioning Systems*. While this was a less than desirable outcome, the effort multiplier for lane-level maps was high enough that the impracticability of lane offset positioning was essentially moot—both were in long range time frame.

However, map optimizations and the emergence of WHICHLANE applications places the ability to position the vehicle in the correct lane in the critical path for WHICHLANE application deployment. It is understood that IMU developments are needed in MEMS gyros to deal with short-term outages, yet baseline WHICHLANE positioning needs to come from GNSS (either differential GPS or Galileo). Figure 5-2 illustrates the possibilities for vehicle positioning capability in the 0.5 – 1 m error range.

The main takeaway point here is that the whether GNSS positioning is achieved via code differential GPS, or dual code Galileo or GPS (future capability), WHICHLANE positioning capability will probably need to come from a class of receiver known as a narrow correlator. Currently, narrow correlator receivers are not OEM affordable as GPS receiver manufacturers are targeting cost, size, and power consumption in the design for products such as cell phones. Accuracy, especially in the range for WHICHLANE positioning, is not a significant concern for high volume GPS receiver manufacturers, and the result is that such receivers are not currently affordable. The situation roadblock is not technological, and can very likely be cleared by increased high volume interest and subsequent production orders of narrow correlator receivers.

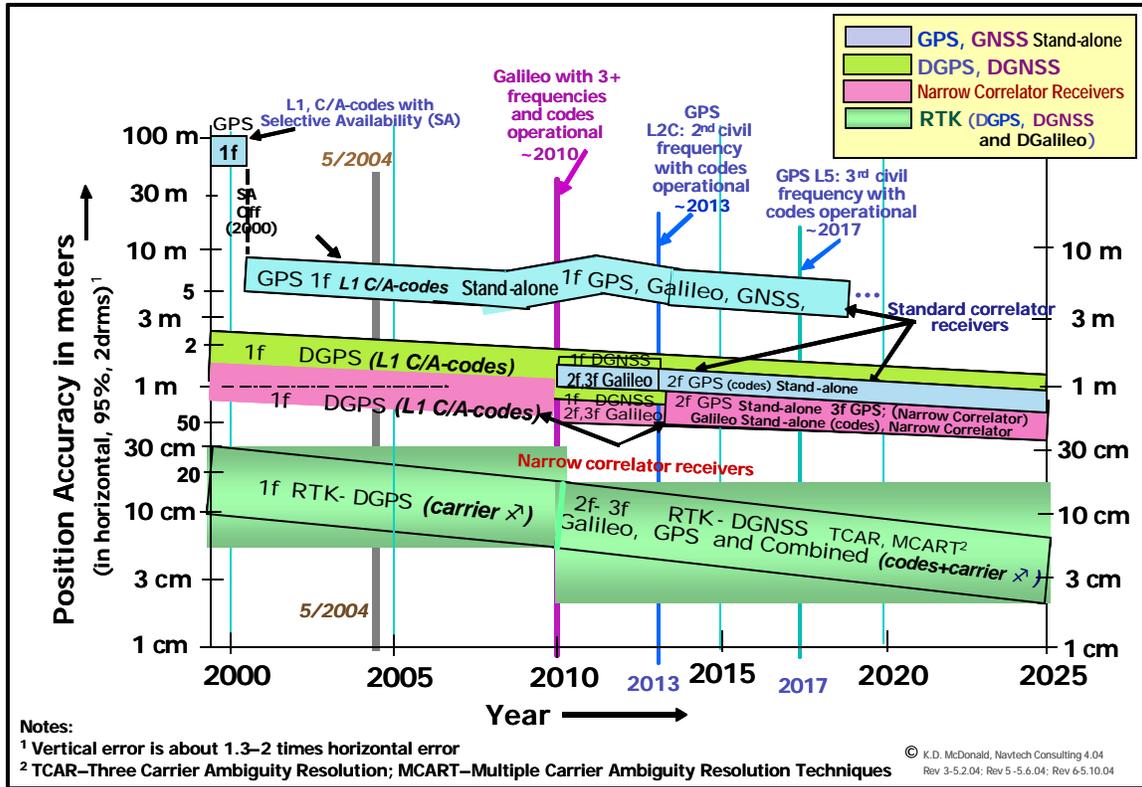


Figure 5-2: GNSS timeline with attention called to 1 to 0.5 m positioning required for WHICHLANE applications

5.4 Applications as a Guide

The use of EDMap applications enabled specific and targeted evaluations that in turn motivated map optimizations and exposed vehicle positioning deployment issues. The applications were a guide to the overall project, and while it could be argued that there are map database uses other than safety that will impact database deployment, one can reasonably argue that restricted focus on safety applications helped keep the EDMap project degrees of freedom from exceeding manageable evaluation limits.

The evaluated EDMap applications exercise the full range of map and vehicle positioning complexity as shown in Table 5-1. The timeline is implicit in a top-down direction where WHATROAD applications are most imminent, WHICHLANE follows, in no particular order, with better vehicle positioning, and finally WHEREINLANE is longer term where reliance on accurate vehicle positioning as well as map accuracy is most demanding.

Table 5-1: Application distribution and potential developmental steps of safety applications

Application Type	Application	Maplet Effort	Positioning Accuracy			
			10-3m	3-1m	1-0.3m	<0.3m
WhatRoad	SSA-W	1.3X				
	CSA-W	1.1X				
WhichLane	SSA-C	1.3X				
	TSA-W	1.3X				
	FCW	1.7X				
	CSA-C	1.2X				
WhereInLane	LDW	1.3X				

5.5 Future Topics

The EDMap project made significant accomplishments toward the production advancement of applications and map databases for vehicle safety. While there is no direct follow-on project planned for EDMap, there are topic areas that can be investigated.

5.5.1 Hybrid Map Database

EDMap developed and tested road and lane-level map databases. As one of the project results, a map database containing both road-level and sections of lane-level was identified as a potential evolutionary step from road-level database to enable applications that only need lanes in areas of road bifurcations, e.g., CSA control and FCW. In such an example, the map would contain road level geometry and attribution on the majority of road segments, and would switch to the lane level map representation near bifurcations or other areas where lane specific information is needed by an application (a WHICHLANE application).

While the prospects of such a hybrid map appear promising, hybrid maps containing both road and lane level were not built and evaluated in EDMap, therefore, such a step is warranted. The reason to consider such a step is that evaluation in the context of an application will likely uncover design challenges previously not addressed. An example for a hybrid map would be the transitions between road-level to lane-level and back to road-level. Map collection and editing techniques will need to ensure smooth transition, and applications will need a maplet interface capable of mixed level map information.

5.5.2 Vehicle Positioning to support WHICHLANE applications

WHICHLANE applications emerged as a grouping of applications requiring vehicle positioning accurate enough to locate the vehicle in the correct lane in the map database. The vehicle positioning requirements do not require the lateral position in lane (as for LDW) to be known, but positioning error must be generally no worse than 1 m to reliably support correct lane placement. As described earlier in the report, EDMap vehicle positioning systems were targeted at the WHAT ROAD and WHEREINLANE levels. No specific testing was performed with a vehicle positioning system with affordable potential specifically at the WHICHLANE level.

A possible future topic would be to perform experiments using differential code based narrow correlator receivers to test the expectation that such receivers can provide reliable WHICHLANE positioning. Participation with GPS receiver companies such as Novatel may be a possible approach for both the experiments as well as product definition for the next generation of narrow correlator receivers that need to be designed to meet vehicle OEM affordability.

5.5.3 Stopping Location Collection and Maintenance using Probe Data

Creating reliable stopping location maplet data for the SSA and TSA applications was problematic in EDMap. The implemented countermeasures for stopping location maplet validation are not bulletproof. Errors of commission and omission, as well as accuracy error, cannot all be captured by the proposed validations. Additionally, database maintenance, particularly when a new stop sign is installed, currently is addressed by either customer feedback or local field office surveys. And finally, the stopping maplet emerged as one of the more “expensive” maplets from the map effort perspective. All these factors point toward improvements in the stopping location maplet collection and maintenance.

5.5.4 Map database update

The aspect of map database maintenance related to the detection of change, primarily via the potential use of probe data has been addressed in this project and suggested as a topic for future work. Current and projected wireless data transfer capabilities have also been reported in the appendices. The investigation and prototyping of delivering fresh map data to the vehicle could be a beneficial future work topic.

Data from probe vehicles is understood to have the potential to be used in many aspects of map database collection and maintenance. The stopping location maplet is ripe with opportunities for map improvements using probe data. Time-spaced probe vehicle positions could be clustered to identify likely stopping locations to address maplet omission and commission errors thereby improving its reliability. Stopping location position accuracy may be enhanced if location can be extracted from the clustered vehicle positions. Using probe data for this specific purpose could be a well defined and clearly containable future work topic.

5.5.5 Quality Indicator Maplet

About halfway through the EDMap project a maplet, called the Quality Indicator (or Quality) maplet, was proposed. It was a new maplet, not part of the original Task 2 scope that was intended to capture map performance to specification at a road segment level of granularity. In other words, each road segment would have a maplet that contained information describing just how good the database was for a particular road segment. The quality maplet was envisioned to provide data such as geometry standard deviations or anticipated error for a given class of point attribute. The idea was to then use the quality maplet in the vehicle application to provide a level of operational reliability.

Currently, and in EDMap as well, quality assessments are/were made based on a composite database area. In practice, some road segments would be very accurate, and others not so accurate, but the overall amalgamation could be within tolerance.

EDMap made some progress with relative accuracy metrics and assessments of accuracy for certain point attributes based on the collection methods. This was a good start, and can enable, for example, an application to create an error model for stopping location based on the collection method assessment. The database quality “polling” technique performed for EDMap is also a good approach to include statistical rigor to the quality assessment, and could be further deployed in the quality maplet construct to sampled areas. More work would need to be done to determine the level of granularity, in terms of area, road, or road section that provides the best benefit with respect to improved application performance reliability.

5.6 Acknowledgements

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