Vehicle-to-Infrastructure Program Safety Applications Project

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16. Abstract

This report describes the development, evaluation and refinement of three Vehicle-to-Infrastructure (V2I) safety applications using Dedicated Short Range Communication (DSRC)-based over-the-air messages between the infrastructure and vehicles. The safety applications selected for development were a Red Light Violation Warning application, Curve Speed Warning application and Reduced Speed Zone Warning with Lane Closure application. The report details the work completed to define system requirements, develop application algorithms and implement the applications in prototype test vehicles. A flexible, containerized Basic Information Message was developed during the project to deliver required infrastructure data to the vehicle-based applications. Six light vehicles and one heavy truck were equipped with the applications and served as the prototype vehicles in testing and stakeholder outreach demonstrations conducted during the project. Portable infrastructure equipment was also developed to support testing and evaluation of the applications. Testing consisted of objective tests conducted on test tracks and engineering tests conducted on public roads. The test results suggested several specific refinements to the applications and underscored the need to conduct additional on-road testing under real-world conditions to further evaluate application performance. The work was conducted by the Crash Avoidance Metrics Partners LLC V2I Consortium through Federal Highway Administration sponsorship. The V2I Consortium consists of Ford, GM, Honda, Hyundai-Kia, Mazda, Nissan, Subaru, VW/Audi and Volvo Truck.

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Table of Contents

Executive Summary **1**

1 Introduction **5**

2 Outreach and Coordination with Stakeholders **7**

2.1 Potential Stakeholders and Partners 7

2.2 Coordination with Stakeholders 8

2.3 Demonstration of Safety Applications to Stakeholders 8

2.4 Collaboration with IOOs to Prioritize and Harmonize Deployment of V2I Applications 9

3 Selection of Safety Applications for Development **10**

3.1 Technical Assessment of Safety Applications 10

3.1.1 Common System Requirements 11

3.1.2 Stop Sign Gap Assist 13

3.1.3 Red Light Violation Warning 17

3.1.4 Curve Speed Warning 20

3.1.5 Reduced Speed Zone Warning 23

3.1.6 Spot Weather Information Warning 24

3.2 Application Selection Criteria 27

3.2.1 Description of Selection Criteria 28

3.3 Application Selection 35

4 Application Development Plan **37**

4.1 Safety Applications and OEM Participation 37

4.1.1 Safety Applications 37

4.1.2 OEM Participation 37

4.2 Selection of Test Locations 38

4.2.1 Red Light Violation Warning 38

4.2.2 Curve Speed Warning 41

4.2.3 Reduced Speed Zone Warning 44

4.3 Vehicle Integration 46

4.3.1 Vehicle Architecture 46

4.3.2 Vehicle Data ... 47
4.3.3 Driver-Vehicle Interface ... 48
4.4 Application Development and Test Plan ... 48
5 Safety Applications – System Architecture ... 50
5.1 In-Vehicle Architecture ... 50
5.1.1 Vehicle Data Interface ... 52
5.1.2 DVI Communication Interface ... 52
5.2 Infrastructure Architecture ... 53
5.2.1 Infrastructure Requirements ... 54
5.3 Wireless Message ... 54
5.3.1 Traveler Information Message ... 54
5.3.2 Basic Information Message Structure ... 55
6 Safety Application Algorithms ... 57
6.1 Event Relevance Assessment Algorithm ... 58
6.2 MAP Matching ... 59
6.3 Warning Assessment Algorithm ... 61
6.3.1 Red Light Violation Warning ... 61
6.3.2 Curve Speed Warning ... 63
6.3.3 Reduced Speed Zone Warning / Lane Closure ... 69
7 Framework for Basic Information Message ... 73
7.1 Common Container ... 73
7.2 Mobile Container ... 75
7.3 Work Zone Container ... 75
7.4 Curve Container ... 76
7.5 Basic Information Message Encoding ... 77
7.6 Minimum Performance Requirements ... 77
7.6.1 General Requirements ... 78
7.6.2 Approaches ... 78
7.6.3 Usage and Example of SegmentedID ... 79
7.6.4 Curve Speed Warning ... 80
7.6.5 Reduced Speed Zone Warning ... 82
8 Vehicle Integration ... 84
8.1 Test Vehicles ... 84

8.2 Test Vehicle Hardware Architecture ... 84
8.2.1 Vehicle Component and Interface Layout ... 84
8.2.2 DVI Interface ... 86
9 Infrastructure Integration / Communication Architecture ... 87
9.1 Compatibility with Integrated V2I Prototype ... 87
9.2 Portable Setup for Base Station for RTCM at Test Locations ... 87
9.3 Support for SPaT and MAP ... 87
10 Objective Test Procedures ... 89
10.1 Test Locations ... 89
10.1.1 Preliminary Tests ... 90
10.1.2 Testing in a Controlled Environment ... 91
10.2 Red Light Violation Warning ... 93
10.2.1 General Test Requirements ... 94
10.2.2 Infrastructure Requirement ... 94
10.2.3 Information Collected During the Test ... 94
10.2.4 Test Documentation ... 94
10.2.5 Test Evaluation – Pass and Fail Criteria ... 95
10.2.6 Test Layout ... 95
10.2.7 Test Layout for Two-Lane Scenario ... 95
10.2.8 Test Layout for Four-Lane Scenario ... 97
10.3 Curve Speed Warning ... 98
10.3.1 General Test Requirements ... 99
10.3.2 Recorded Data Element ... 99
10.3.3 Test Documentation ... 100
10.3.4 Test Setup and Layout – Single Radius Curve ... 100
10.3.5 Test Evaluation – Pass and Fail Criteria ... 100
10.4 Reduced Speed Zone / Lane Closure Warning ... 101
10.4.1 General Test Requirements ... 101
10.4.2 Infrastructure Requirement ... 102
10.4.3 Recorded Data Element ... 102
10.4.4 Test Documentation ... 102
10.4.5 Test Layout ... 102
10.4.6 Required Tests Performed ... 104
10.4.7 Test Evaluation – Pass and Fail Criteria ... 104

11 Results and Analysis of Objective Tests 105

11.1 RLVW Test Results and Analysis 105

11.1.1 Test 1: Reach Intersection on Red 106

11.1.2 Test 2: Stop at Intersection 107

11.1.3 Test 3: Right Turn on Green 109

11.1.4 Test 4: Multiple Intersections within 300 m 109

11.1.5 Test 5: Reach Intersection When Signal Turns Red 109

11.1.6 Test 6: Reach Intersection When Signal Turns Green 111

11.1.7 Test 7: Approach Lane Matching (Edge of Lane) 113

11.1.8 Test 8: Right Turn on Red 113

11.1.9 Test 9: Late Lane Change 114

11.1.10 Test 10: Turn on Yellow 114

11.1.11 Analysis of Additional RLVW Tests Conducted at the Test Facility at the University of Michigan 114

11.2 CSW Test Results and Analysis 120

11.2.1 Test 1: Inform and Warning Verification – Single Radius Curve, Dry Road 122

11.2.2 Test 2: Warning Suppression – Single Radius Curve, Dry Road 123

11.2.3 Test 3: Inform and Warning Verification – Single Radius Curve, Icy Road 124

11.2.4 Test 4: Inform and Warning Verification – Single Radius Curve, Reduced Visibility 125

11.2.5 Multiple Radii Curve Tests 126

11.2.6 Analysis of Additional CSW Tests at the Test Facility at the University of Michigan 131

11.3 RSZW/LC Test Results and Analysis 135

11.3.1 Tests 1 and 6: Reduced Speed 136

11.3.2 Tests 2 and 7: Reduced Speed when Workers Present 137

11.3.3 Tests 3 and 8: One Lane Closure 138

11.3.4 Tests 4 and 9: Two Lane Closures 139

11.3.5 Tests 5 and 10: Two Lane Closures and Reduced Speed 140

11.4 Observations and Lessons Learned 141

11.4.1 Red Light Violation Warning 141

11.4.2 Curve Speed Warning 142

11.4.3 Mapping Requirements for Reduced Speed Zone / Work Zone / Lane Closure Warning 143

12 Automatic Intersection Map Generation 145

13 Feasibility Assessment for Actuated Traffic Signal Control 146
13.1 Basic Operation of a Traffic Signal 146
13.2 Elements of a Traffic Signal Timing 149
13.3 Pedestrian Intervals 153
13.4 Existing Red Light Violation Warning Applications 154
13.5 Impact of Different Traffic Signal Operations on Red Light Violation Warning Applications 155
14 CSW and RSZW Engineering Testing on Public Roads 156
14.1 CSW On-Road Testing 156
14.1.1 Analysis of Conducted CSW Tests 159
14.1.2 Analysis of CSW Test Results 166
14.2 RSZW/LC On-Road Testing 167
14.2.1 Identified Work Zones for RSZW/LC On-road Tests 167
14.2.2 Evaluation of Work Zone Area 167
14.2.3 RSZW/LC Test Scenario 169
14.2.4 RSZW/LC Test Evaluation 169
14.2.5 Analysis of RSZW/LC Test Results 171
15 Summary 172
16 References 175
APPENDIX A. List of Acronyms 177
APPENDIX B. Superelevation and Pavement Crowns 181
APPENDIX C. ASN.1 Structure for BIM 182
APPENDIX D. Objective Tests for Red Light Violation Warning Application 186
D.1 Test 1: Reach Intersection on Red 186
D.1.1 Test Goal 186
D.1.2 Test Script 187
D.1.3 Tests Conducted 188
D.1.4 Test Evaluation – Pass and Fail Criteria 188
D.2 Test 2: Stop at the Intersection 189
D.2.1 Test Goal 189
D.2.2 Test Script 189
D.2.3 Tests Conducted 189

D.2.4 Test Evaluation – Pass and Fail Criteria 190
D.3 Test 3: Right Turn on Green 191
D.3.1 Test Goal 191
D.3.2 Test Script 191
D.3.3 Tests Conducted 192
D.3.4 Test Evaluation – Pass and Fail Criteria 192
D.4 Test 4: Multiple Intersections within 300 m 193
D.4.1 Test Goal 193
D.4.2 Test Script 193
D.4.3 Tests Conducted 194
D.4.4 Test Evaluation – Pass and Fail Criteria 194
D.5 Test 5: Reach Intersection When Signal Turns Red 195
D.5.1 Test Goal 195
D.5.2 Test Script 195
D.5.3 Tests Conducted 195
D.5.4 Test Evaluation – Pass and Fail Criteria 196
D.6 Test 6: Reach Intersection When Signal Turns Green 197
D.6.1 Test Goal 197
D.6.2 Test Script 197
D.6.3 Tests Conducted 197
D.6.4 Test Evaluation – Pass and Fail Criteria 198
D.7 Test 7: Approach Lane Matching (Edge of Lane Testing) 199
D.7.1 Test Goal 199
D.7.2 Test Script 199
D.7.3 Tests Conducted 200
D.7.4 Test Evaluation – Pass and Fail Criteria 200
D.8 Test 8: Right Turn on Red 201
D.8.1 Test Goal 201
D.8.2 Test Script 201
D.8.3 Tests Conducted 202
D.8.4 Test Evaluation – Pass and Fail Criteria 202
D.9 Test 9: Late Lane Change 203
D.9.1 Test Goal 203
D.9.2 Test Script 203

D.9.3 Tests Conducted 204
D.9.4 Test Evaluation – Pass and Fail Criteria 204
D.10 Test 10: Reach Intersection on Yellow 205
D.10.1 Test Goal 205
D.10.2 Test Script 205
D.10.3 Tests Conducted 206
D.10.4 Test Evaluation – Pass and Fail Criteria 206
D.11 Additional RLVW Tests – Test Facility at the University of Michigan 207
D.11.1 Association Validation Test 208
D.11.2 Application Validation – Right Turn Signal Indicator OFF 209
D.11.3 Application Validation – Right Turn Signal Indicator ON 209
D.11.4 Application Validation – Warning Suppression 210
D.11.5 Application Validation – Left Turn Signal Indicator On 211

APPENDIX E. Objective Test Procedures for Curve Speed Warning Application 212

E.1 Test 1: Inform and Warning Verification – Single Radius Curve, Dry Road 212
E.1.1 Test Goal 212
E.1.2 Test Setup 213
E.1.3 Test Script 213
E.1.4 Tests Conducted 213
E.2 Test 2: Warning Suppression – Single Radius Curve, Dry Road 214
E.2.1 Test Goal 214
E.2.2 Test Setup 214
E.2.3 Test Script 215
E.2.4 Tests Conducted 215
E.2.5 Test Evaluation – Pass and Fail Criteria 216
E.3 Test 3: Inform and Warning Verification – Single Radius Curve, Icy Road 216
E.3.1 Test Goal 216
E.3.2 Test Setup 217
E.3.3 Test Script 217
E.3.4 Tests Conducted 217
E.4 Test 4: Inform and Warning Verification – Single Radius Curve, Reduced Visibility 218
E.4.1 Test Goal 218
E.4.2 Test Setup 218

E.4.3 Test Script ... 219
E.4.4 Tests Conducted ... 219
E.5 Tests 5 and 6 Setup and Layout – Multiple Radii Curve ... 220
E.5.1 Test 5: Inform and Warning Verification – Multiple Radii Curve, Dry Road ... 221
E.5.2 Test 6: Inform and Warning Verification – Multiple Radii Curve, Icy Road ... 223
APPENDIX F. Objective Test Procedures for Reduced Speed Zone Warning / Lane Closure Application ... 226
F.1 Tests 1 and 6: Reduced Speed ... 226
F.1.1 Test Goal ... 226
F.1.2 Test Setup ... 226
F.2 Tests 2 and 7: Reduced Speed When Workers Present ... 227
F.2.1 Test Goal ... 227
F.2.2 Test Setup ... 227
F.3 Tests 3 and 8: One Lane Closure ... 228
F.3.1 Test Goal ... 228
F.3.2 Test Setup ... 228
F.4 Tests 4 and 9: Two Lane Closures ... 228
F.4.1 Test Goal ... 228
F.4.2 Test Setup ... 229
F.5 Tests 5 and 10: Lane Closures and Reduced Speed ... 229
16.1.1 Test Goal ... 229
16.1.2 Test Setup ... 230

List of Figures

Figure 1: Vehicle and Infrastructure Components for V2I Safety Applications 10

Figure 2: Information Flow for V2I Safety Applications 11

Figure 3: SSGA Application Concept Illustration 13

Figure 4: Information Flow for SSGA Application 14

Figure 5: SSGA Application Option 2 15

Figure 6: SSGA Application Option 2 – Pass Through and Vehicle Determination Approaches 16

Figure 7: RLVW Application Concept Illustration 18

Figure 8: Information Flow for RLVW Application 18

Figure 9: CSW Application Concept Illustration 21

Figure 10: Information Flow for CSW Application 21

Figure 11: Approaching a Curve in CSW 22

Figure 12: RSZW-RS/LC Application Concept Illustration 23

Figure 13: Information Flow for RSZW-RS/LC Application 24

Figure 14: SWIW-D/RS Concept Illustration 25

Figure 15: Information Flow for SWIW-D/RS 26

Figure 16: Aerial View of Telegraph Road and W. 12 Mile Road, Southfield, Michigan 39

Figure 17: Street View of W. 12 Mile Road at Telegraph Road, Southfield, Michigan 39

Figure 18: Aerial View of Telegraph Road and W. 10 Mile Road, Southfield, Michigan 40

Figure 19: Street View of Telegraph Road at W. 10 Mile Road, Southfield, Michigan 40

Figure 20: Aerial View of Interstate 75 South of 9 Mile Road, Hazel Park, Michigan 42

Figure 21: Aerial View of I-94 and M-10 Freeway Interchange, Detroit, Michigan 43

Figure 22: Aerial View of Hills Tech Drive at Haggerty Road, Farmington Hills, Michigan 44

Figure 23: Street View of Hills Tech Drive from Haggerty Road, Facing East 45

Figure 24: Street View of Farmington Road at W. 13 Mile Road with Lane Closure 45

Figure 25: Safety Application In-Vehicle Architecture 47

Figure 26: Safety Application Development and Testing Timeline 49

Figure 27: High-Level System Architecture for DSRC-based V2I Safety Applications 50

Figure 28: In-Vehicle Architecture Block Diagram 51
Figure 29: Block-Diagram of the Infrastructure System Architecture 54
Figure 30: Basic Information Message Structure 56
Figure 31: Safety Application Algorithm Components 57
Figure 32: Graphical Representation of Event Zones 58
Figure 33: Flowchart for Determining Zone Relevance 59
Figure 34: MAP Matching Algorithm Flowchart 60
Figure 35: Illustration of MAP Matching Process 60
Figure 36: Turn/Lane Prediction Algorithm Flowchart for RLVW 62
Figure 37: Curve Speed Warning Algorithm Flowchart 65
Figure 38: Example of Warning Distances Determination for CSW 69
Figure 39: Warning Level Assessment Algorithm Flowchart for RSZW/LC 70
Figure 40: Graphical Example of Layout of Approach and Geometry Lanes 79
Figure 41: Graphical Example of Usage of SegmentedID 80
Figure 42: Example Approach to a Curve Event 80
Figure 43: Example - Placement of Reference Point and First Node Point of Approach and Curve Geometry 81
Figure 44: Test Vehicles for Safety Applications 84
Figure 45: Hardware Component Layout 85
Figure 46: Picture of Integrated Hardware in a Test Vehicle 86
Figure 47: Satellite Images of the FTTA Proving Ground – (a) Access to the Test Facility and (b) Layout of Test Tracks 92
Figure 48: Satellite Images of the Test Facility at the University of Michigan and Test Areas for RLVW and CSW 93
Figure 49: Layout for Two-Lane Scenario 95
Figure 50: Flag Placement for Two-Lane Scenario – 55 mph Approach Speed 96
Figure 51: SPaT for Tests 1 Through 6 and 9 96
Figure 52: SPaT for Test 10 97
Figure 53: Layout for Four-Lane Intersection Scenario 97
Figure 54: Flag Placement for Four-Lane Scenario – 55 mph Approach Speed 98

Figure 55: SPaT for Tests 7 and 8 98
Figure 56: Test Layout for Tests 1 Through 4........ 100
Figure 58: Test Layout for 45 mph Approach Speed........ 104
Figure 59: RLVW Test 1 – Warning and Distance to Stop Bar 106
Figure 60: RLVW Test 1 – Warning State and Current Signal Phase 107
Figure 61: Summary of RLVW Test 1 107
Figure 62: RLVW Test 2 – Warning and Distance to Stop Bar, with Brake Status........ 108
Figure 63: RLVW Test 2 – Warning State and Current Signal Phase, with Brake Status 108
Figure 64: Summary of RLVW Test 4 109
Figure 65: RLVW Test 5 – Warning and Distance to Stop Bar, with Brake Status........ 110
Figure 66: RLVW Test 5 – Warning State and Current Signal Phase, with Brake Status 110
Figure 67: Summary of RLVW Test 5 111
Figure 68: RLVW Test 6 – Warning and Distance to Stop Bar, with Brake Status........ 112
Figure 69: RLVW Test 6 – Warning State and Current Signal Phase, with Brake Status 112
Figure 70: Summary of RLVW Test 6 113
Figure 71: Summary of RLVW Test 8 114
Figure 72: Lane and Signal Phase Association Validation Test........ 115
Figure 73: Application Validation – Right Turn Signal Indicator NOT Activated........ 116
Figure 74: Warning Status – Right Turn Signal Indicator NOT Activated........ 117
Figure 75: Application Validation – Right Turn Signal Indicator Activated........ 118
Figure 76: Warning Status – Right Turn Signal Indicator Activated........ 118
Figure 77: Application Validation – Late Activation of Right Turn Signal Indicator 119
Figure 78: Warning Status – Late Activation of Right Turn Signal Indicator 119
Figure 79: Application Validation – Left Turn Signal Indicator Activated 120
Figure 80: Warning Status – Left Turn Signal Indicator Activated 120
Figure 81: Example of a CSW Test Result........ 122
Figure 82: CSW Test 1 - Single Radius Curve, Dry Road........ 123
Figure 83: CSW Test 2 – Warning Suppression, Single Radius Curve 124
Figure 84: CSW Test 3 – Single Radius Curve, Icy Road........ 125

Figure 85: CSW Test 4 – Single Radius Curve, Reduced Visibility 126
Figure 86: Radii of Node Segments for Tests 5 and 6 127
Figure 87: CSW Test 5 – Multiple Radii Curve, Dry Road 129
Figure 88: Speed Difference vs. Warning Time Difference 129
Figure 89: CSW Test 6 – Multiple Radii Curve, Icy Road 131
Figure 90: Time and Distance to Approaching Node Segment for Single Warning 131
Figure 91: CSW Test Layout at the Test Facility at the University of Michigan 132
Figure 92: Composite Graph of 12 CSW Test Runs 134
Figure 93: Discontinuation of Warning 135
Figure 94: RSZW/LC Test 1 and Test 6 – Reduced Speed at 70 mph and 45 mph 137
Figure 95: RSZW/LC Test 2 and Test 7 – Reduced Speed when Workers Present at 70 mph and 45 mph 138
Figure 96: RSZW/LC Test 3 and Test 8 – One Lane Closure at 70 mph and 45 mph 139
Figure 97: RSZW/LC Test 4 and Test 9 – Two Lane Closures at 70 mph and 45 mph 140
Figure 98: RSZW/LC Test 5 and Test 10 – Two Lane Closures, Reduced Speed when Workers Present at 70 mph and 45 mph 141
Figure 99: Example Approach Scenarios for CSW 143
Figure 100: Example of RSZW/LC Lane Mapping Scenario 144
Figure 101: Basic Components of a Traffic Signal 147
Figure 102: Typical Operating Modes for Traffic Signals 148
Figure 103: Example of Daily Fluctuation in Traffic Signal Operations 149
Figure 104: NEMA Movement Phase Numbering Scheme 150
Figure 105: Intervals within a Vehicle Phase 151
Figure 106: Pedestrian Intervals 153
Figure 107: Location of Selected Curves for On-road Testing of CSW 157
Figure 108: Test Curve #3, Test Vehicle – Hyundai-Kia Test Run 1 161
Figure 109: Test Curve #3, Test Vehicle – Hyundai-Kia Test Run 2 161
Figure 110: Test Curve #4, Test Vehicle - Audi 162
Figure 111: Test Curve #5, Test Vehicle - Audi 163

Figure 112: Test Curve #6, Test Vehicle - Audi ... 164

Figure 113: Test Curve #6, Test Vehicle – Audi, “Geometry Retry” ... 164

Figure 114: Test Curve #7, Test Vehicle - Buick ... 165

Figure 115: Test Curve #7, Test Vehicle - Buick, “Geometry Retry” ... 165

Figure 116: Test Curve #7, Test Vehicle - Buick, “Geometry Retry,” Warning Discontinued ... 165

Figure 117: Rectangular Bounding Box for Map Matching Zone ... 166

Figure 118: RSZW/LC Work Zone Map ... 168

Figure 119: Mounted RSU Near the Work Zone ... 168

Figure 120: Test Vehicle Driven on the Left Most Lane (Closing Lane) ... 170

Figure 121: Test Vehicle Driven on the Left Center Lane ... 170

Figure 122: Map Matching “Geometry Retry” While the Test Vehicle is Changing Lane ... 171

Figure 123: RLVW Test 1 Scenario ... 186

Figure 124: RLVW Test 1 Geometry – 35 mph Approach Speed ... 187

Figure 125: RLVW Test 1 Geometry – 70 mph Approach Speed ... 187

Figure 126: RLVW Test 2 Scenario Geometry ... 189

Figure 127: RLVW Test 3 Scenario Geometry ... 191

Figure 128: RLVW Test 4 Scenario Geometry ... 193

Figure 129: RLVW Test 5 Scenario Geometry ... 195

Figure 130: RLVW Test 6 Scenario Geometry ... 197

Figure 131: RLVW Test 7 Scenario Geometry ... 199

Figure 132: RLVW Test 8 Scenario Geometry ... 201

Figure 133: RLVW Test 9 Late Lane Change Scenario ... 203

Figure 134: RLVW Test 10 Yellow Phase Approach Scenario ... 205

Figure 135: SPaT for Conducted Tests ... 208

Figure 136: RLVW Tests Scenario Geometry ... 208

Figure 137: Setup and Layout for Tests 5 and 6 ... 220

Figure 138: Detailed Geometry for Tests 5 and 6 ... 220

List of Tables

Table 1: V2I Safety Application General Requirements and Data Elements 12

Table 2: Proposed SSGA Application Options 14

Table 3: Criteria for Representative V2I Safety Application Build Selection 28

Table 4: List of Participating OEMs for Safety Applications 38

Table 5: Test Sites for RLVW Application 41

Table 6: Test Sites for CSW Application 43

Table 7: Test Sites for RSZW Application 46

Table 8: Safety Application Development and Test Plan 48

Table 9: List of Configuration Parameters for Turn Prediction Algorithm 63

Table 10: Rate of Superelevation as a Function of Radius of the Curved Road 66

Table 11: Roadway Surface Friction Coefficient 67

Table 12: Computation of V_{max} 67

Table 13: Data Elements for RSZW/LC Algorithm 71

Table 14: RSZW/LC Algorithm Output 72

Table 15: Data Elements for a Common Container 73

Table 16: Data Elements for a Mobile Container 75

Table 17: Data Elements for a Work Zone Container 75

Table 18: Data Elements for the Curve Container 76

Table 19: Summary of Tests Conducted 89

Table 20: Preliminary Tests Sites 90

Table 21: RLVW Test Scenarios 93

Table 22: CSW Test Scenarios 98

Table 23: RSZW/LC Test Scenarios 101

Table 24: Flag Locations for 70 mph Approach Speed 103

Table 25: Flag Locations for 45 mph Approach Speed 104

Table 26: RLVW Test Summary 105

Table 27: CSW Test Summary 121

Table 28: Node Points and Computed Segment Radii for Tests 5 and 6..... 126

Table 29: Computed Vmax Speed for Test 5 128

Table 30: Computed V_{max} Speed for Test 6 130

Table 31: Test Runs Conducted CSW Tests at the Test Facility at the University of Michigan 132

Table 32: Summary of CSW Tests Conducted at the Test Facility at the University of Michigan..... 133

Table 33: Computed V_{max} Speed for CSW Tests at the Test Facility at the University of Michigan 133

Table 34: RSZW/LC Test Summary..... 135

Table 35: Characteristics of Selected Curves with Calculated V_{max} 157

Table 36: Conducted Test Runs 160

Table 37: Test Runs Conducted for Test 1..... 188

Table 38: Test Runs Conducted for Test 2..... 190

Table 39: Test Runs Conducted for Test 3..... 192

Table 40: Test of Multiple Intersections within 300 m for Test 4 194

Table 41: Test Runs Conducted for Test 5..... 196

Table 42: Test Runs Conducted for Test 6..... 198

Table 43: Test Runs Conducted for Test 7..... 200

Table 44: Test Runs Conducted for Test 8..... 202

Table 45: Test Runs Conducted for Test 9..... 204

Table 46: Test Runs Conducted for Test 10 206

Table 47: Test Runs Conducted for Test 1..... 214

Table 48: Test Runs Conducted for Test 2..... 215

Table 49: Test Runs Conducted for Test 3..... 217

Table 50: Test Runs Conducted for Test 4..... 219

Table 51: Test Runs Conducted for Test 5..... 223

Table 52: Test Runs Conducted for Test 6..... 225

Executive Summary

The overall objective of the Vehicle-to-Infrastructure Safety Applications (V2I-SA) Project was to develop and evaluate a portfolio of V2I safety applications to demonstrate that communication from infrastructure to vehicle can be brought to bear for improved safety. The applications included a Red Light Violation Warning (RLVW), a Curve Speed Warning (CSW) and a Reduced Speed Zone Warning with Lane Closure (RSZW/LC). This report describes the work completed in Tasks 1 through 12 of the project, which spanned project inception in September 2014 through June 30, 2017. The V2I-SA Project was conducted by the Crash Avoidance Metrics Partners LLC (CAMP) V2I Consortium and supported by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH611H0002, Work Order 0003. The CAMP V2I Consortium consists of Ford, General Motors, Hyundai-Kia, Honda, Mazda, Nissan, Subaru, Volvo Technology of America, and VW/Audi.

Presently, many infrastructure-based countermeasures have been implemented by public agencies and vehicle-based countermeasures have been implemented by vehicle Original Equipment Manufacturers (OEMs), both for the purpose of improving safety. These systems, until recently, have not typically integrated both infrastructure and vehicle data. Integrating roadside infrastructure and vehicle data in such systems may deliver more robust information for identifying driving hazards and providing drivers with more accurate and timely warnings of potentially unsafe roadway conditions.

The project initially considered five V2I safety applications for potential further development. These applications were: RLVW, Stop Sign Gap Assist (SSGA), CSW, Spot Weather Information Warning (SWIW), and RSZW/LC. Various deployment attributes and project impact factors were assessed for each of the five safety applications and a set of application selection criteria were developed. The selection criteria also leveraged the National Connected Vehicle Field Infrastructure Footprint Analysis [1] as well as inputs from the FHWA project staff. The findings formed the RLVW, CSW and RSZW/LC applications as the portfolio of applications for further development in the project.

The requirements, architecture, and algorithms for the selected applications were then developed, including both in-vehicle and infrastructure systems. Guidelines for the development and implementation of the in-vehicle subsystems along with the minimum performance criteria for the algorithms were also defined. Common algorithms were developed that were designed to work for both light vehicles and heavy-duty vehicles. The algorithms were modified as needed to incorporate the vehicle dynamics associated with the heavy-duty vehicles. Another important project outcome was the design of an infrastructure-based Dedicated Short-Range Communications (DSRC) over-the-air message, referred to in this project as the Basic Information Message (BIM). The overriding purpose of the BIM was to provide the transmission of needed V2I safety applications data elements from infrastructure in a single message. The new message structure was needed because some of the needed data elements to support the applications were not available in existing V2I or Vehicle-to-Vehicle (V2V) message structures.

Six light vehicles and one heavy truck were selected as test vehicles. All seven vehicles were built with the three prototype safety applications. To the extent possible, common hardware components were used across the seven vehicles. Necessary testing of the on-board software and hardware systems was done to ensure correct system functionality on the vehicle side of the applications.

An infrastructure build featured the development of portable roadside equipment that could conveniently be transported to a test track and quickly set up to support testing of the three safety applications. The equipment included traffic signals, a traffic signal controller, Global Positioning System (GPS) base station equipment with Radio Technical Commission for Maritime Services (RTCM) corrections, and a roadside unit (RSU) capable of transmitting Signal Phase and Timing (SPaT) information and encoded intersection map data. The designed BIM message for the CSW and RSZW/LC applications was implemented in the RSU. Multiple site surveys were conducted to prepare encoded maps (in SAE J2735 MAP format) for the test sites used in the project. Functional testing of the infrastructure equipment was conducted, as was interoperability testing between the infrastructure equipment and the in-vehicle equipment.

Testing and evaluation of the three applications was conducted on both test tracks and public roads. Initially, objective tests were conducted on a test track to assess application performance and implement improvements to the applications. Later, engineering tests of the CSW and RSZW/LC application were conducted under real-word conditions on public roads.

More than twenty distinct scenarios were designed for the objective testing to assess and document system performance against requirements. More than one hundred test runs were conducted using both the light- and heavy-duty vehicles over a period of eleven months. The test scenarios and algorithm parameters were modified as necessary to incorporate the vehicle dynamics associated with both light- and heavy-duty vehicles. Table ES-1 provides an overview of the vehicle, road/traffic parameters, and infrastructure-based message combinations that were tested. In addition to standard SPaT, SAE J2735 Map (MAP) and RTCM messages, the BIM information specific to the CSW and RSZW/LC applications was implemented and successfully tested.

Table ES-1: Overview of Tests Conducted during Objective Tests

		Test Vehicles		Road / Traffic Parameters							
V2I Safety Applications	I2V Message	Passenger	Commercial	Road Surface Type	Surface Friction Coefficient	Curvature	Super elevation	Visibility	Multiple Lanes	Lane Closures	Presence of Workers
RLVW	SPaT / MAP / RTCM	✓	✓						✓		
CSW	BIM	✓	✓	✓	✓	✓	✓	✓			
RSZW/LC	BIM	✓	✓						✓	✓	✓

Source: CAMP – V2I Consortium

The initial objective tests were conducted in a controlled environment at the FT Techno of America (FTTA) Proving Ground, Fowlerville, Michigan. Test layouts for two- and four-lane intersections for RLVW and dual-radii curvature for CSW were facilitated on the dynamics pad. A three-lane construction zone with two lane closures was set up on a straight roadway for RSZW/LC. Test conditions and outcomes of the objective tests are presented in Table ES-2.

Table ES-2: Summary of Objective Testing Outcomes

Safety Application	No. of Conducted Test Runs / Scenarios	Percent of Successful Test Runs	Reason for Unsuccessful Test Runs	Conclusion
RLVW	81 test runs 10 test scenarios	62%	Failed to synchronize start of the test runs with proper signal phase Improper map matching for a lane with permissible multiple movements	Update algorithm to address turn prediction based on vehicle turn signal indicator with appropriate signal phase association for lanes with multiple movements
CSW	89 test runs 6 test scenarios	83%	The late Inform was due to delayed map matching of the approach lane caused by incorrect placement of cones The late Warning occurred when vehicle speed was marginally higher than the computed maximum speed (Vmax)	Update algorithm to address warning when vehicle speed is up to 11 mph higher than the computed V_{max}
RSZW/LC	82 test runs 5 test scenarios at 45-70 mph	100%		All test runs generated Inform and Warning within prescribed range, including suppression of Warning for lane closure based on vehicle turn signal indicator

Source: CAMP – V2I Consortium

Following the initial objective tests and detailed data analysis, the RLVW and CSW algorithms were further refined and additional tests were conducted to validate their performance. The RLVW algorithm was enhanced to support a single lane that can be associated with multiple signal phases that allow multiple movements. For CSW, the algorithm was modified for warning generation when the vehicle speed slightly exceeded (11 mph or less) the computed speed for the curve. In that case, the algorithm will generate only the Warning 1 and suppress the Warning 2 that would have occurred within less than a second. The revised applications were tested at the test facility at the University of Michigan using the objective test procedures to re-verify the performance of the applications against the requirements.

On-road engineering testing of CSW on public road and RSZW/LC in a live work zone were also conducted during the project to examine application performance in real-world conditions. Nearly 75 on-road test runs of CSW were conducted on five different freeway exit and entrance ramps of varying multi-radii curves to assess this application's performance. Similarly, nine test runs for the RSZW/LC were conducted in a freeway construction zone. In both applications, the analysis indicated that the applications performed as intended. In some test runs for CSW, however, when the test vehicles were driven outside the mapped lane (i.e., on the lane shoulder), the application could not determine vehicle's position on the lane, causing a failure in map matching. This was corrected by describing the shoulder as the part of the lane in the map. In the case of the RSZW/LC application, data anomalies were noted in some test runs in which the location of the Inform/Warning messages presented to the driver was displaced from the expected location. The anomalies were attributable to a shift in the reference point resulting from dynamic changes in the work zone configuration which no longer matched the map installed in the RSU. Proper and accurate infrastructure maps are, therefore, imperative for the correct functioning of the V2I applications.

Throughout the project, the V2I Consortium interacted and coordinated with various entities to exchange information needed for the development of the applications, coordinate test plans, and support outreach for future deployment of the applications. To this end, the Consortium engaged in activities with the U.S. Department of Transportation (USDOT), Michigan DOT, V2I Deployment Coalition, the Infrastructure Owners and Operators (IOO) forum, and Society of Automotive Engineers (SAE) DSRC Technical Committee. Two technology demonstrations (April 2016 and January 2017) were held for V2I stakeholders during the project to showcase the developed applications.

The current RLVW implementation developed in this project is designed to support pre-timed (fixed) signal timing values where signal operations are not based on detection. Pre-timed signal controllers encompass a significant percentage of the traffic signal locations in the U.S. A feasibility study was conducted in conjunction with the Texas Transportation Institute (TTI) to assess whether the existing RLVW application would support actuated traffic signals, and if not, what work would be needed to include actuated traffic signals in the RLVW application. The study concluded that the algorithm should function as intended at intersections operating under actuated control, coordinated control, or signal preemption. This is a direct result of the existing RLVW application only issuing alerts during the yellow and red portions of the signal phase. These two signal phases are fixed intervals and do not vary from cycle to cycle, irrespective of the operating mode of the traffic signal.

Finally, to overcome the drawbacks of manual intersection site surveys, the project also examined an approach for automatically generating an intersection map (in SAE J2735 MAP format) using Basic Safety Messages (BSMs) received by RSUs. This was work was conducted in collaboration with the University of Michigan Transportation Research Institute (UMTRI) and is being reported separately. [2] Overall, the approach demonstrated the feasibility and potential of using BSM and SPaT data to automatically generate intersection maps and phase-lane association mapping.

To take the outcome of this research to real-world deployment, several research efforts could be pursued in the future; two were identified in this project and are recommended for future work. While the current project focused on using static map generation, safety applications could be dramatically affected by temporary changes in roadway configuration due to such things as a lane closure, road construction or traffic incidents. It would be beneficial to investigate the feasibility of automatically generating and updating dynamic maps, in near real-time, for transmitting in the DSRC message to vehicles. A second effort would address future large-scale real-world deployment by providing procedures and tools to verify completeness and correctness of transmitted messages from the infrastructure. Such tools would be beneficial to organizations tasked with undertaking future systems deployments. Generation of dynamic maps and verification of transmitted DSRC messages are necessary elements for developing and deploying effective and robust applications to assist drivers in a connected transportation environment.

1 Introduction

The objective of the Vehicle-to-Infrastructure Safety Applications (V2I-SA) Project was to develop and test a portfolio of V2I safety applications that focused on infrastructure interaction and deployment. Several safety applications were initially considered for study in the project and included Red Light Violation Warning (RLVW), Emergency Vehicle Priority Warning (EVPW), Curve Speed Warning (CSW), Spot Weather Impact Warning (SWIW), Reduced Speed Zone Warning with Lane Closure (RSZW/LC) and Stop Sign Gap Assist (SSGA). The RLVW, CSW and RSZW/LC applications were selected for development based on assessments conducted in the project and discussions with the Federal Highway Administration (FHWA) project staff. This report describes the work completed to design, develop, test, evaluate and refine the three applications using prototype vehicles and prototype infrastructure equipment also developed during the project. In addition, demonstrations of the developed applications were made to selected stakeholders and industry representatives to foster information exchanges between the project and organizations that could potentially deploy the technology in the future.

The project was conducted by the Crash Avoidance Metrics Partners LLC (CAMP) V2I Consortium. The companies participating in the V2I Consortium are Ford, General Motors, Hyundai-Kia, Honda, Mazda, Nissan, Subaru, Volvo Technology of America, and VW/Audi. The project was sponsored by the FHWA through Cooperative Agreement DTFH611H0002, Work Order 0003.

Organization of the Report

This report describes the work completed in Tasks 1 through 12 of the project from inception in September 2014 through June 30, 2017. Task 1 was the technical project management task which ran throughout the project.

Chapter 2 outlines the activities and initiatives undertaken to support outreach during the project and coordination with important stakeholders. This effort was contained within Task 2 of the project.

Chapter 3 describes the selection of the three safety applications for development. The work conducted included a technical assessment of potential safety applications, development of application selection criteria and application of the criteria to select the applications for further development. This effort was contained in Tasks 3 and 4.

Chapter 4 details the work plan to develop and evaluate the three prototype V2I safety applications selected. This work was conducted during Task 5 in the project. The plan established the timeline, milestones, deliverables and allocation of responsibilities across V2I Consortium Participants and contracted suppliers, covering activities up to the start of field testing.

Chapters 5, 6 and 7 discuss the design and development of the safety applications. These three chapters, respectively, present the systems architecture, application algorithm design and a framework for a Basic Information Message to transmit needed data from the infrastructure to the vehicle-based applications. The work presented in Chapters 5, 6 and 7 was contained in Task 6 of the project.

The vehicle integration work is described in Chapter 8 while the infrastructure integration work is detailed in Chapter 9. During the project, the integration work was conducted in Task 7 (vehicles) and in Task 8 (infrastructure).

The initial testing and refinement of the applications was conducted in Task 9 of the project. This work has been divided into two chapters for reporting purposes. Chapter 10, in conjunction with Appendices D, E and F, present the objective test procedures used to verify application performance. Chapter 11 presents the summary of the tests conducted, analysis of data and results.

Task 10 of the project featured a stand-alone task to examine the feasibility of developing an automated method of producing intersection maps to support the RLVW application using Basic Safety Messages (BSMs) received by an intersection Roadside Unit (RSU). The results of this work are being reported separately [2]. Only a summary of the automated map generation work is provided in Chapter 12.

Chapter 13 presents an assessment of the RLVW application developed in the project to identify the application’s compatibility with actuated traffic signal control. The application, as initially developed, was implemented for pre-timed signals. This work was conducted in Task 11 of the project.

Chapter 14 presents the results of engineering tests conducted on public roads with the CSW and RSZW/LC applications to gain further insights into application performance that could not be assessed on a test track. Task 12 of the project contained this work.

Chapter 15 contains the project summary.

2 Outreach and Coordination with Stakeholders

The goals of the stakeholder coordination and outreach activities were to initially identify potential stakeholders and partners for the safety applications and subsequently engage the identified organizations, as needed, to complete the project. Specific objectives for this effort included:

- Exchange information with the stakeholders about the development of the selected applications that could beneficially affect development of the applications and the infrastructure build
- Exchange knowledge and lessons learned from developing and testing selected safety applications
- Conducting limited application performance evaluations in real-world driving environments
- Potentially assist with infrastructure setup and verification

This chapter presents the list of partners and stakeholders initially identified and the major engagements undertaken during project execution.

2.1 Potential Stakeholders and Partners

The following organizations were identified as potential stakeholders and partners:

- Battelle and Noblis – FHWA contractors - Partner
- American Association of State Highway and Transportation Official (AASHTO) – Stakeholder
- Institute of Transportation Engineers (ITE) – Stakeholder
- U.S. Department of Transportation (USDOT) Intelligent Transportation System (ITS) Joint Program Office (JPO) implementing Connected Vehicle Reference Implementation Architecture (CVRIA) – Partner
- V2I Deployment Coalition – Stakeholder
- Infrastructure Owners and Operators (IOOs) – Stakeholder
- Michigan Department of Transportation (MDOT) – Stakeholder
- Road Commission of Oakland County (RCOC) – Stakeholder
- Society of Automotive Engineers (SAE) – Stakeholder

2.2 Coordination with Stakeholders

During the design, development and testing stages of the safety applications in this project, several meetings were held with stakeholders and external entities to exchange information to support project execution. These are discussed below.

The initial engagement with MDOT occurred during the development and testing of the CSW application to identify roadway curves in Southeast Michigan that have a higher propensity for motorist to run off the curve. The interaction was also discuss the methods MDOT used to provide information about the roadway characteristics such as road surface material and condition, coefficient of friction, superelevation and radius of curvature. Discussions were also held with MDOT for placement of a roadway sensor (i.e., an Environmental Sensor Station) for detecting and receiving roadway surface condition from an RSU. As the application development and testing progressed, interaction continued for supporting test and evaluation of the work zone warning application in live work zone. In 2016, MDOT, in collaboration with the project Technical Management Team (TMT), developed a work zone map and installed an RSU on a trailer in a construction zone on I-75 in Southeast Michigan for conducting performance evaluations of the RSZW/LC application in a live work zone. The on-road testing efforts undertaken with support from MDOT are described in detail later in the report. Collaboration with MDOT also continued to support signalized intersection for Signal Phase and Timing (SPaT)/MAP broadcast verification.

During CSW and RSZW/LC application development, the need for a new Dedicated Short Range Communications (DSRC) over-the-air (OTA) message was identified because the data elements needed to support these applications were not available in existing V2I or V2V message structures contained in the SAE J2735 standard. The new message developed in the project, referred to as the Basic Information Message (BIM), is described in Chapter 7. Presentations were subsequently conducted with FHWA/Noblis and SAE to present the rationale and need for the message as well as provide performance results from testing with the BIM using project test vehicles.

Presentations were also made to the V2I Deployment Coalition Working Group 3 regarding the RSZW/LC application for work zone and CSW.

2.3 Demonstration of Safety Applications to Stakeholders

On April 19-22, 2016, the three V2I safety applications developed in the project were demonstrated at a test track in Fowlerville, Michigan. The applications showcased were the RLVW, CSW and RSZW/LC applications. During the four-day event, representatives from V2I Deployment Coalition, the USDOT Connected Vehicle Pilot sites, the Smart City Challenge finalists, the OEMs and USDOT experienced the prototype safety applications in test vehicles and a heavy-duty truck. Over 200 participated in the demonstration.

A second demonstration event was also conducted on January 24-25, 2017 as part of the events surrounding the Washington, DC auto show. The demonstration was held in a parking lot at the RFK Stadium. Like the first demonstration event, the operation of the RLVW, CSW and RSZW/LC applications were presented in short, ride-along sessions in equipped test vehicles. The event participants included representatives from the U.S. and state DOTs, congressional staff, the Government Accountability Office (GAO), OEMs and media. Over 125 participated in the demonstration event.

2.4 Collaboration with IOOs to Prioritize and Harmonize Deployment of V2I Applications

Members of the V2I DC who attended the April 2016 demonstrations advocated for increasing the communications between IOOs and OEMs to facilitate development of V2I safety applications and foster their future deployment. The concept of a workshop was discussed as the next appropriate step to begin this two-way communication. An initial workshop, facilitated by FHWA at Turner Fairbanks Highway Research Center, was held on September 22-23, 2016 to develop a process for the two groups to work together to enable applications envisioned for a connected vehicle environment.

Subsequently, a forum comprised of select automotive OEMs, IOOs, and USDOT representatives was established to coordinate and evaluate deployments of V2I applications across the U.S. IOOs believe DSRC-based technologies will be first integrated into traffic light controllers because of ease of installation and maintenance. High penetration rate and adoption by the automotive OEMs and the society will make this technology sustainable and scalable. With this in mind, IOOs will undertake deployment of V2I applications in phases and coordinate with each other and automotive OEMs. Four areas were prioritized and working groups were formed to support each initiative. The working groups and their goals are:

1. SPaT/RLVW Working Group - Encourage all agencies deploying SPaT/MAP to validate their deployments
2. RSZW/LC Working Group – Facilitate the transition of RSZW/LC applications from the test environment to the real-world
3. Connected Automation Working Group - Focus on the developing Eco Approach and Departure and Cooperative Adaptive Cruise Control (CACC) applications
4. Multi-Modal Intelligent Traffic Signal Systems (MMITSS) – Focus on continued development of MMITSS 3 within the Connected Vehicle Pooled Fund Study (CV PFS) and identify CAMP and USDOT representatives to participate in the development efforts

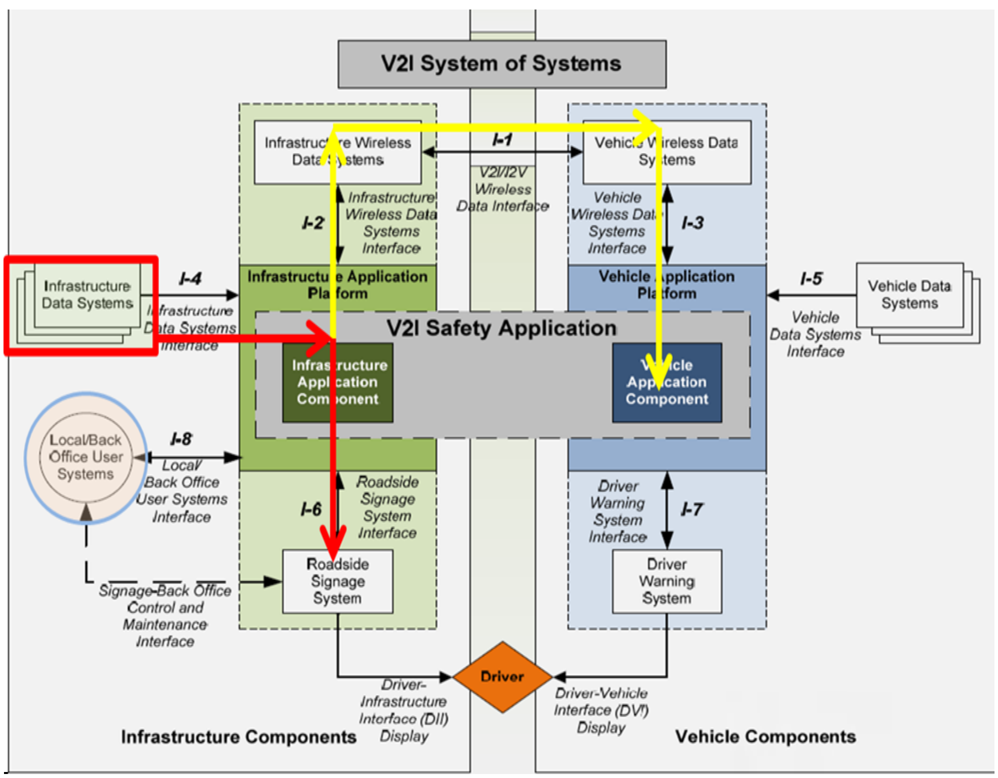
The V2I-SA Project Team has supported these groups since their inception and contributed information leading to the development of three-, six-, and nine-month plans for the working groups. In addition, representatives from the V2I-SA Project are leading the SPaT/RLVW Working Group and actively participate in the SPaT Challenge resource team meetings and RSZW Working Group. The V2I-SA Project has also provided an intersection verification document to the SPaT/RLVW Working Group for review. It is anticipated that work with the IOO / OEM forum will continue to facilitate deployment of V2I safety applications.

3 Selection of Safety Applications for Development

The initial work in the project focused on technical assessments of five safety applications considered for further development in the project. These were: RLVW, SSGA, CSW, SWIW, and RSZW/LC. The assessments included a review of the systems engineering documents developed in prior work by Battelle for FHWA as background information for an OEM-evaluation of the feasibility, benefits, and issues associated with implementation. The technical assessment and resulting selection of three applications for further development is presented in this chapter.

3.1 Technical Assessment of Safety Applications

A V2I safety application can be analyzed in terms of an infrastructure component and a vehicle component, as shown in Figure 1. The two subsystems share data via a DSRC-based communication system. The highlighted red path shows the data flow from the Infrastructure Data Systems (IDS) to the infrastructure application component, which is located along the roadside. The data flow from the infrastructure application component to the vehicle application component is highlighted in yellow.

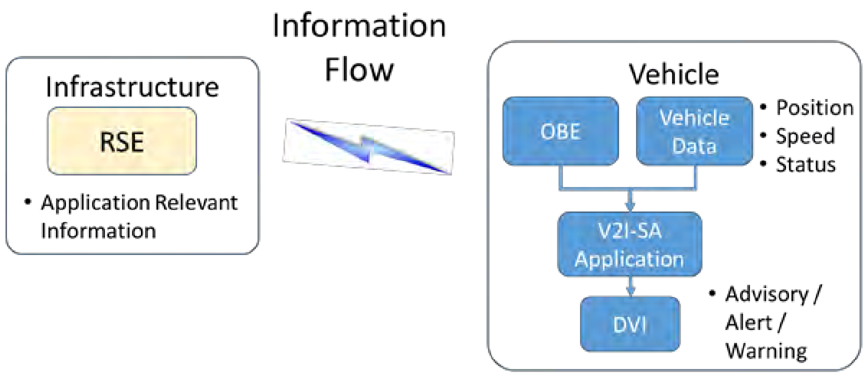


Source: Battelle (Stephens et al., 2015, FHWA Report No. FHWA-JPO-15-254, p. 10)

Figure 1: Vehicle and Infrastructure Components for V2I Safety Applications

3.1.1 Common System Requirements

The following sections describe the elements for implementing the V2I safety applications from an automotive OEM perspective with emphasis given to the inputs needed for the vehicle-side of the application. Figure 2 depicts the common requirements for the information flow between the infrastructure Roadside Equipment (RSE) and the vehicle On-Board Equipment (OBE) over the DSRC-based communication link.



Source: CAMP – V2I Consortium

Figure 2: Information Flow for V2I Safety Applications

The general requirements along with the application specific system and data elements are listed in Table 1.

Table 1: V2I Safety Application General Requirements and Data Elements

		Safety Applications						
	Description	SSGA	RLVW	CSW	RSZW-RS	RSZW-LC	SWIW-D	SWIW-RS
General Requirements								
	Road Level Localization	√	√-S	√	√		√	√
	Lane Level Localization		√-C	O		√		
	Field and Vehicle Equipment Time Synchronization using Coordinated Universal Time (UTC)	√	√					
V2I-SA Data Elements - RSE								
	Geometric Intersection / Roadway Description (GID)	√	√	√	√	√	√	√
	Road Curvature Information			√				
	Road Elevation Information			O				
	GPS/RTCM Correction		O	O		O		
	Signal Phase and Timing(SPaT)		√					
	Posted Speed Limit	O	O	O	√	√	O	O
	Posted Advisory Speed			O				√
	Vehicle Detection on Major Roadway	√						
	Vehicle Speed	√						
	Vehicle Distance	√						
	Vehicle Heading (Direction of Travel)	√						
V2I-SA Data Elements - Vehicle								
	Vehicle Speed	√	√	√	√	√	√	√
	GPS (Lat, Lon, Alt, Heading, etc.)	√	√	√	√	√	√	√
	Longitudinal Acceleration		√	√	O			O
	Brake Status		√	√				
	Lateral Acceleration			O				
	Turn Signal Status	√	√	O		√		
	Steering Wheel Angle		√	O		√		
	Yaw Rate		√	O		√		
√ - Required, O - Optional								
√-S - Required for simple intersection without dedicated turn lane								
√-C - Required for complex intersection with dedicated turn lane								

Source: CAMP – V2I Consortium

The SSGA application requires detection of the number of vehicles, their speeds and headings on the major roadway. RLVW application requirements depend upon the type of intersection. At a simple intersection with no dedicated turn lanes, a road-level localization is sufficient. At a complex intersection with one or more dedicated turn lanes, lane-level positioning is required by the application to determine the appropriate criteria to apply and avoid providing false information to the driver.

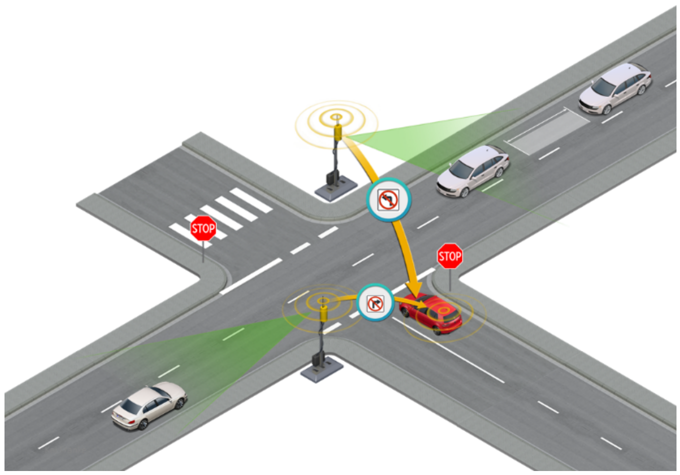
In addition, the following general requirements were identified in the technical assessment:

- Secure communication between the back office and the RSE
- Secure communication between the RSE and the OBE in the vehicle
- Appropriate application-relevant Driver-Vehicle Interface (DVI)
- Infrastructure support for unequipped vehicles through the Driver-Infrastructure Interface (DII)

The subsections that follow describe proposed safety application and associated technical assessment for the proposed five applications.

3.1.2 Stop Sign Gap Assist

The objective of the SSGA application is to provide alerts and warnings to drivers at a stop sign-controlled intersection about potentially unsafe gaps due to approaching cross-traffic and thus assist in crossing the intersection through cross traffic as shown in Figure 3.



Source: CAMP – V2I Consortium

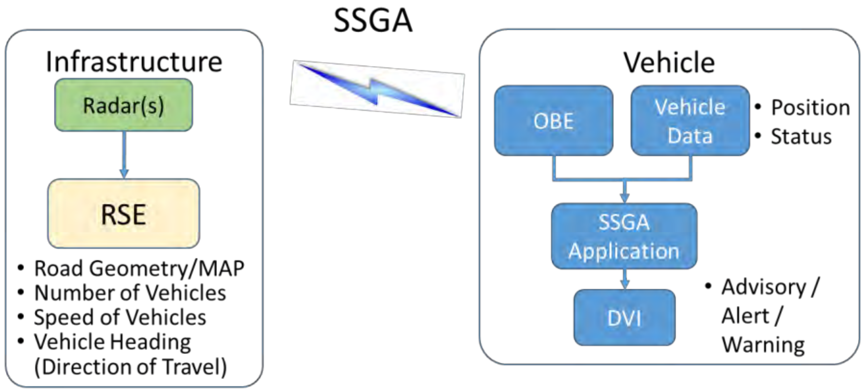
Figure 3: SSGA Application Concept Illustration

3.1.2.1 Functional Behavior

Upon approaching the intersection, the subject vehicle on a minor roadway would receive a stop ahead advisory. While the subject vehicle is at the stop bar, the infrastructure application component would provide data to the vehicle application component for:

- An advisory that cross traffic does not stop
- An alert to approaching traffic from the left side or the right side
- A warning of approaching traffic from the left side or the right side

The information flow for the SSGA application is depicted in Figure 4.



Source: CAMP – V2I Consortium

Figure 4: Information Flow for SSGA Application

Based on the specification provided, the infrastructure application component shall at a minimum receive the position (with road-level accuracy) and speed of the vehicles on the major road from the infrastructure sensors. This data could be provided by radar sensors placed at the roadside. If the major road allows for traffic in both directions and/or has multiple lanes, multiple radar sensors might be necessary.

The infrastructure application component collects information from these radar sensors. Based on the information derived, appropriate DSRC messages are generated in the RSE to inform the driver of the vehicle on the minor road about the current status of the traffic approaching the intersection and associated gaps in the traffic. The vehicle application component in the OBE considers additional vehicle status inputs such as vehicle position, speed and turn signal to provide appropriate advisory/warning messages.

For conducting the technical assessment for this application, application performance requirements [3], system performance requirements [4] and application Concept of Operations (ConOps) [5] documents were reviewed. The proposed SSGA application can be deployed in the following modes as shown in Table 2.

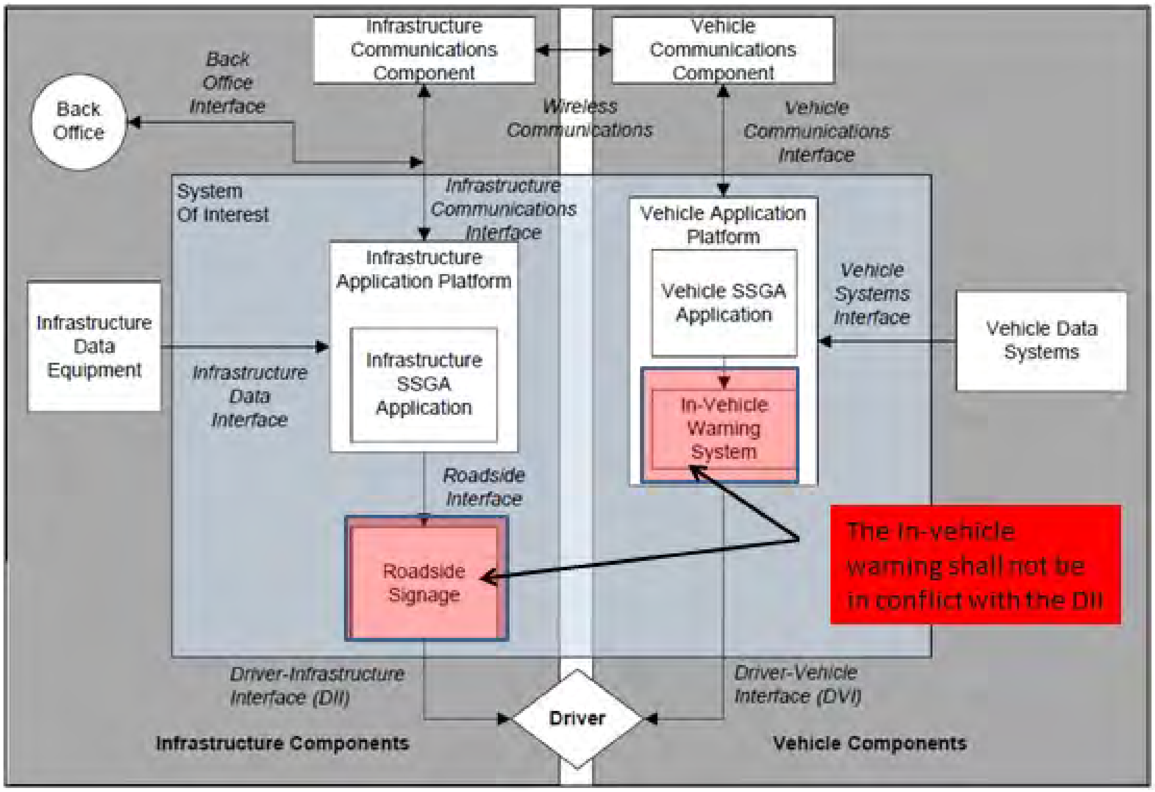
Table 2: Proposed SSGA Application Options

		Infrastructure Equipment			Vehicle Technology		Server
			Radar	Weather	Minor Vehicle	Major Vehicle	Intersection
Option	SSGA Application	RSE	System	Sensors	VEHICLE 1	VEHICLE 2	Description
1	Roadside only		X				
2	Roadside + Minor	X	X		Equipped		
3	Roadside + Minor + Major	X	X	X	Equipped	Equipped	
4	Roadside + Minor + Major + Server	X	X	X	Equipped	Equipped	X

Source: CAMP – V2I Consortium

Options 1 and 2 are considered the basic modes of the application and do not require large deployment rates of DSRC-equipped vehicles. Option 1 is an infrastructure-only solution and requires no equipped vehicles. The gap detection is performed using roadside sensors and the infrastructure application component generates messages for the driver using a DII. In Figure 5, Option 2 uses the same detection technique for equipped vehicles waiting at minor roads. In this case, the application in the equipped vehicle can receive DSRC messages and inform the driver using the in-vehicle DVI.

Options 3 and 4 expand the application further with the addition of equipped vehicles on major roads. In Option 3, Basic Safety Messages (BSMs) received from these vehicles by the RSE could be fused with vehicle tracks collected from the infrastructure sensors to potentially improve performance. The benefits of this option would evolve as the penetration rate of infrastructure and vehicles increases. Option 4 incorporates additional data gathered from weather sensors to improve the advisory/warning calculation and to factor in roadway conditions for improved gap calculation. As an example, an alert may be issued sooner than usual in icy road conditions.



Source: Battelle (Stephens et al., 2012, FHWA Report No. FHWA-JPO-12-059, p. 10)

Figure 5: SSGA Application Option 2

3.1.2.2 Assessing the Warning Systems

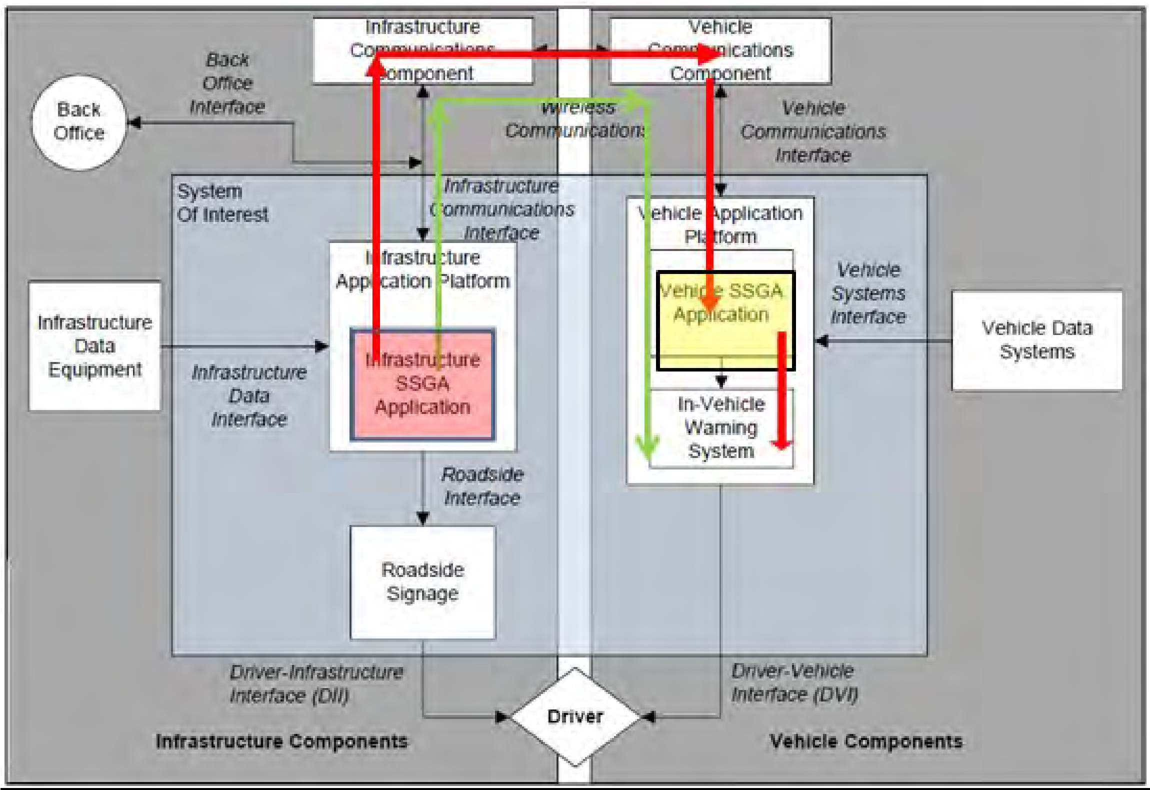
To avoid driver confusion, the in-vehicle driver notification system should not conflict with roadside signage. However, methods to achieve this harmonization will require further review.

Figure 6 illustrates two approaches to provide an In-Vehicle Warning:

- Pass through Advisory: The alert/warning is calculated by the infrastructure application component and forwarded to the vehicle in real time. No additional calculation in the vehicle takes place.

- Vehicle Determination: In parallel to the infrastructure the vehicle also receives information about the status of the intersection and information about the position, speed and heading of other vehicles. The vehicle application component then calculates advisory and warning information.

The risks to be assessed in selecting the appropriate approach to be used include latency, unmatched control algorithms and unmatched warnings.



Source: Battelle (Stephens et al., 2012, FHWA Report No. FHWA-JPO-12-059, p. 10)

Figure 6: SSGA Application Option 2 – Pass Through and Vehicle Determination Approaches

3.1.2.3 Technical Assessment of SSGA

The items listed below require further research.

- Research is necessary to determine whether in-vehicle (DVI) warnings and infrastructure (DII) warnings should be independently calculated or simply handled as pass through from infrastructure application component to the vehicle application component allowing quick synchronization of the Advisory, Alert and Warnings. It is unlikely that vehicle and infrastructure application component algorithms can be matched, so a pass-through solution may be necessary
- The additional safety benefits of providing an in-vehicle application component in addition to an infrastructure application component are not known. For example, if a driver looking

straight ahead can see the functioning DII, what value is added by providing a matched DVI?

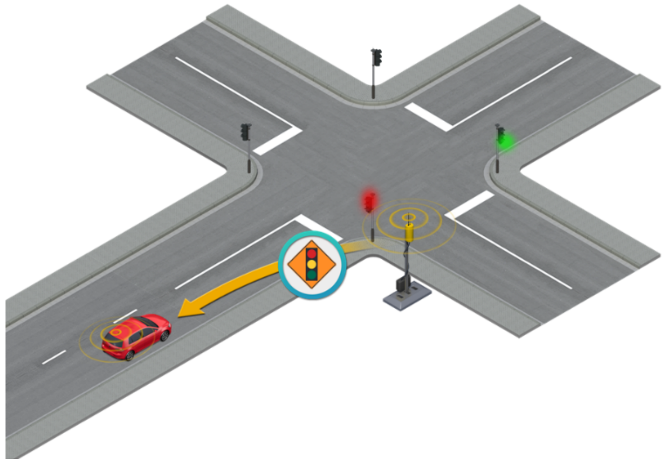
- The application considers only road-level positioning information for vehicles on a major road. In the case of roads with multiple lanes, this could generate false warnings for a driver on a minor road intending to turn right. For example, a single vehicle approaching the intersection from the left would lead to a message from the application that a right turn is currently not safe. If that vehicle was driving on the leftmost lane and it was the intention of the driver on the minor road to turn right onto the rightmost lane the warning would not have been necessary. In scenarios such as these, lane-level position information could improve the performance of the application.
- The application relies on radar sensors mounted on the roadside. Further research is needed to determine if and how these systems can be protected against weather influence (snow or ice) and accidental or intentional damage.
- System performance could be limited under heavy rain or snow conditions. The system would require the capability to perform continuous self-diagnosis to determine if the sensor systems are performing properly, which could have an impact on maintenance costs.

3.1.3 Red Light Violation Warning

The objective of the RLVW application is to advise drivers of an upcoming signalized intersection and warn them, based on data from infrastructure and vehicle-based sensors, if they are at risk of violating a red signal phase if they do not stop.

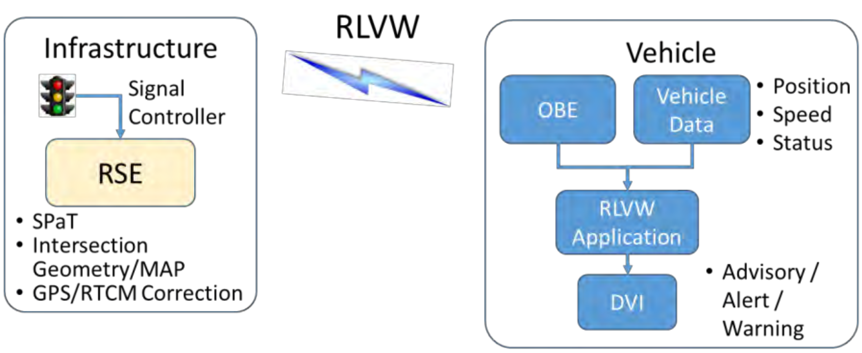
3.1.3.1 Functional Behavior

RLVW receives SPaT information from the infrastructure RSE and combines it with vehicle kinematic data to determine the potential to violate a red signal phase at an approaching signalized intersection. Driver notifications are based on available SPaT information, intersection geometry, real-time road and weather conditions and vehicle dynamics. The RLVW application concept is illustrated in Figure 7. The infrastructure application component provides information to the vehicle application component, which generates vehicle-specific advisories, alerts and warnings to notify the driver in sufficient time to stop before entering the intersection on a red phase thus avoiding a potential red light violation. The information flow for the RLVW application is shown in Figure 8.



Source: CAMP – V2I Consortium

Figure 7: RLVW Application Concept Illustration



Source: CAMP – V2I Consortium

Figure 8: Information Flow for RLVW Application

The high-level system requirements for the RLVW application include:

- For the infrastructure:
  - As shown in Figure 8, the infrastructure consists of the traffic light signal controller and the RSE
  - The traffic light signal controller provides information regarding the SPaT of all the approaches/lanes in the intersection to the RSE
  - The RSE transmits intersection information using a MAP message as defined in SAE J2735

  - The RSE uses the information from the traffic signal controller, associates it to the lanes defined in the MAP for the intersection, and constructs and transmits the SPaT message as defined in SAE J2735 for each approach.
  - The RSE may also be configured to transmit local Global Positioning System (GPS) / Radio Technical Commission for Maritime Services (RTCM) correction messages to provide additional positional accuracy to vehicles
- For the vehicle:
  - OBE configured to receive and interpret MAP/SPaT messages from the RSE
  - The OBE uses vehicle position, dynamics information, and MAP/SPaT information to perform application threat analysis
  - OBE and OEM-specific DVI to inform the driver about application threats when identified
  - The OBE may use GPS/RTCM corrections when available to improve its positional accuracy

3.1.3.2 Technical Assessment of RLVW

This subsection provides the technical assessment for the infrastructure and vehicle application components of RLVW based on review of the application performance requirements [6], system performance requirements [4] and application ConOps [5] documents.

The following aspects of the infrastructure-side application component require further consideration and/or investigation:

- Infrastructure message transmission policies such as message transmission rate, transmission channel (i.e., fixed or channel-switching) and transmission power through RSE
- Handling and transmitting local traffic control policies specific to an intersection (e.g., right turn on red during specified times of a day)
- The convention to be followed to assign a unique Intersection ID for an intersection (duplication of Intersection IDs may lead to complications in the vehicle-side application component)
- The factors influencing changes to adaptive signal timing controllers and the implications for the vehicle-side application component
- Future enhancements to the infrastructure-side application component enabled by supplying the infrastructure RSE with additional information from the back office (e.g., as weather conditions, road surface coefficient)

The following aspects of the vehicle-side application component require further consideration and/or investigation:

- Additional data to correlate braking levels with the braking distance and local weather conditions

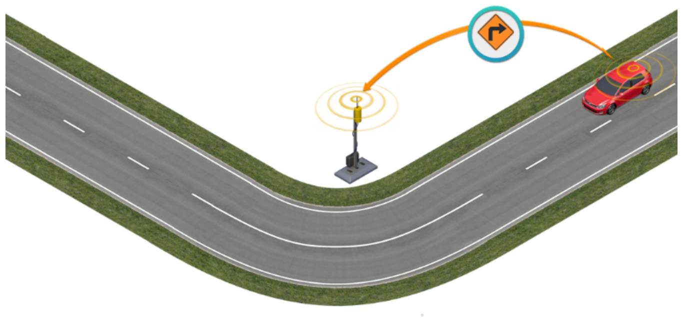
- The improvement in positional accuracy with the help of local GPS/RTCM corrections, the time required to incorporate these corrections once received and the impact on application during this time.
- The potential to anticipate driver intent in situations where GPS/RTCM corrections are not available (thus vehicle position cannot be established at lane-level) by observing vehicle status such as turn indicator, brake status, steering wheel angle, or yaw rate and applying heuristics. For example, in the case where the signal phase is red for through traffic and green for left or right turn lanes, an alert or warning need not be issued if it can be inferred that the driver is in a turning lane.
- Detection of vehicles making a legal right turn on red and suppressing potential false positive warnings
- Driver's reaction to alerts/warnings in the "dilemma zone" and the effect on following traffic. (The dilemma zone is the period which begins with the traffic light changing from green to yellow and the point when the driver decides to either brake to a stop before the intersection or continue through the intersection.)
- Vehicle speeds higher than the average speed for an intersection (perhaps up to 20%) and the implications of such factors as RSE communication range limits or the ability to predict driver intent (i.e., turning vs. straight passing through) at longer ranges
- Variation in application performance between rural and urban settings resulting from differences in GPS availability
- The use of road/weather condition information to adapt application parameters (e.g., braking threshold)

3.1.4 Curve Speed Warning

The objective of the CSW application is to leverage V2I communication to provide drivers an alert and/or warning if the vehicle's current speed may be unsafe to traverse one or more upcoming curves based on vehicle and environmental conditions.

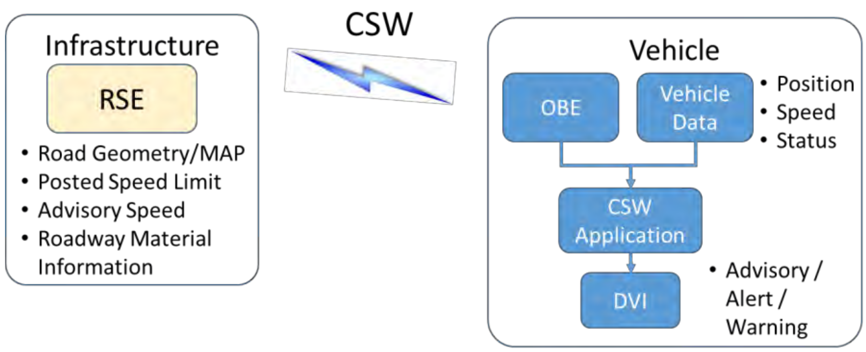
3.1.4.1 Functional Behavior

When an equipped vehicle is approaching a curve, the driver first encounters static (or fixed) curve speed signage advising the driver of an impending curve. The vehicle application component will subsequently trigger a sequence of advisory, alert and/or warning messages that will be displayed to the driver on an in-vehicle warning system. Figure 9 summarizes the CSW application concept. The information flow for the CSW application is shown in Figure 10.



Source: CAMP - V2I Consortium

Figure 9: CSW Application Concept Illustration



Source: CAMP – V2I Consortium

Figure 10: Information Flow for CSW Application

3.1.4.2 Technical Assessment of CSW

This subsection provides the technical assessment for the infrastructure and vehicle application components of CSW based on review of the application performance requirements [7], system performance requirements [4] and application ConOps [5] documents.

The CSW application faces several challenges as outlined in the following sections.

3.1.4.2.1 Relevance Calculation

When the vehicle approaches the curve as shown in Figure 11, the vehicle application component needs to identify whether the vehicle is approaching the curve or if it is passing the curve on an adjacent lane. This is especially relevant for curves that are located behind forks. For example, the left lane might continue on a highway, whereas the right lane represents an off-ramp that leads to a curve that would require a warning. In this situation, a lane-level map of the lane leading to the curve might be required. Furthermore, lane-level localization accuracy in the vehicle application component might be beneficial in reducing false positives and false negatives. Other locations that do not include a fork-like separation might not require lane-level accuracy.

Source: © 2016 Google Map Data. Used with permission.

Figure 11: Approaching a Curve in CSW

3.1.4.2.2 Determination of Appropriate Warning Speeds

The application should issue warnings tailored to the specifics of road geometry, road conditions and vehicle capabilities. To do so will require that it collect the necessary information and calculate an appropriate speed based on these factors. In cases where not all the variables are known, one possible approach would be to assume potentially unsafe conditions exist. While this ensures that the warnings are issued under all conditions, it will lead to false positive warnings in situations where the conditions are better than the conservative assumption. This could result in driver annoyance and subsequent reduction of the benefits of the application if the driver ignores future warnings.

3.1.4.2.3 Timely Warnings

It must be ensured that the vehicle-side application receives the necessary information at a point where the issuing of a warning enables the driver to reduce the vehicle speed before entering the curve. For a vehicle approaching the curve, an in-vehicle algorithm will calculate the appropriate speed for this specific vehicle to traverse the curve. This speed will then be compared to the current vehicle speed to provide the proper advisory or warning to the driver. Based on data or assumptions on the deceleration capabilities of the driver, different advisory or warning messages would be issued.

This consideration will lead to indications on appropriate RSE placement. A worst-case scenario can be assumed where a vehicle with very low curve speed capabilities (e.g., a loaded truck) approaches a curve at or even above the speed limit. This vehicle would have to decelerate significantly (also considering possibly lower deceleration capabilities) which leads to a large required warning distance. The architecture of the application requires the vehicle to receive a DSRC message transmitted by the infrastructure RSE before performing these calculations. Assuming the in-vehicle algorithm shows no significant latencies, the vehicle needs to reliably receive the message at the distance to the curve where the first advisory/warning message will be issued. Based on typical DSRC message reception rates over distance and considering the infrastructure message transmission rate, the optimal placement of the RSE can be calculated for a specific location.

Additional data elements that could be beneficial in calculating an appropriate curve speed are:

- Infrastructure Data Elements
    - Curve geometry to calculate curvature values
        - Super elevation

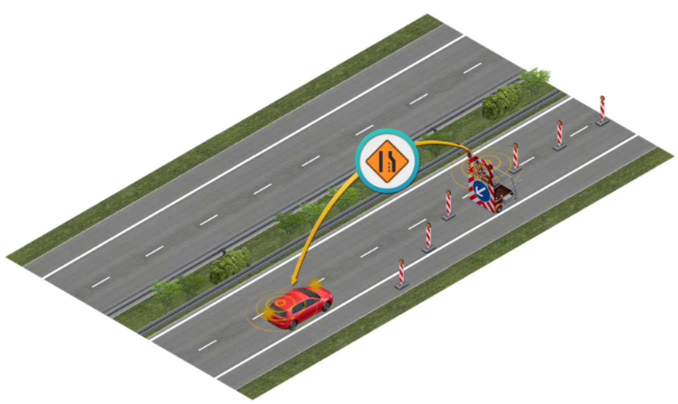
        - Slope
    - Posted curve speed, if present
    - Road surface characteristics (e.g., material used, age of road)
    - Weather conditions (e.g., temperature, precipitation)
- Vehicle Data Elements
    - Location
    - Speed
    - Heading
    - Brake system capabilities
    - Weight
    - Height and position of center of gravity

3.1.5 Reduced Speed Zone Warning

The objective of the RSZW application is to leverage V2I communication to warn drivers when they are operating at a speed higher than the posted speed limit and/or by providing information regarding changes in roadway configuration (e.g., lane closures, lane shifts), particularly for a driving scenario requiring a lane change. This may aid in reducing the number and severity of roadway injuries and or property damage associated with roadway incidents.

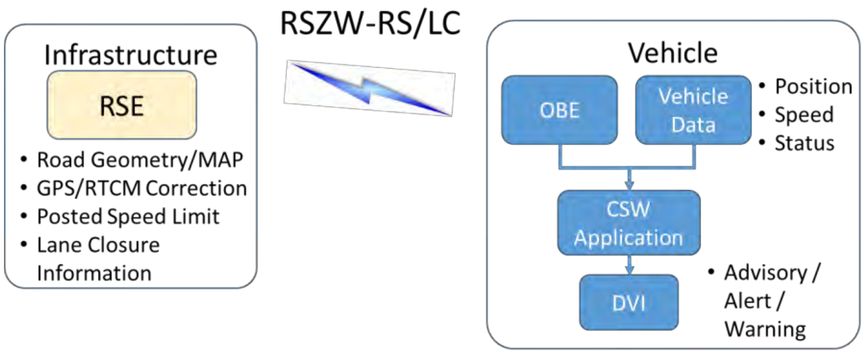
3.1.5.1 Functional Behavior

An equipped vehicle approaching a reduced speed zone is issued an advisory, alert and/or warning message if the vehicle application component determines that the driver is at risk of an incident based on current speed and/or changes in the roadway environment. As an example, a message containing work zone information is sent from the RSE to the OBE. Such information includes the work zone speed limit and geometric configuration, including lane closure information. Figure 12 illustrates the RSZW application concept. The RSZW application information flow is shown in Figure 13.



Source: CAMP – V2I Consortium

Figure 12: RSZW-RS/LC Application Concept Illustration



Source: CAMP – V2I Consortium

Figure 13: Information Flow for RSZW-RS/LC Application

The RSZW application can be implemented as two options:

- RSZW/Reduced Speed (RS): This application addresses reduced speed warnings and issues an advisory or warning message to the driver based on the vehicle speed and location relative to the reduced speed zone. If the vehicle is at an advance warning distance (as provided in the Manual on Uniform Traffic Control Devices (MUTCD) [8]) from the work zone, an advisory message can be displayed on the DVI. If the vehicle speed is greater than the work zone speed limit, an advisory or warning message is shown on the DVI based on the distance from the work zone.
- RSZW/Lane Closure (LC): This application addresses lane closures in work zone areas. The DVI will show an advisory or warning message to the driver based on the vehicle's traffic lane and location relative to the work zone. An advisory of lane closure ahead is displayed on the DVI system within an advance warning (as provided in MUTCD [8]) distance from the work zone. A warning is displayed on the DVI if the driver does not change lanes and is at risk of unsafe driving based on vehicle speed and distance from the work zone.

3.1.5.2 Technical Assessment of RSZW-RS/LC

This subsection provides the technical assessment for the infrastructure and vehicle application components of RSZW-RS/LC based on review of the application performance requirements [9], system performance requirements [10] and application ConOps [11] documents.

The RSZW-RS/LC safety application alerts the driver to two scenarios, reduced speed and lane closures, the latter imposing the need for lane-level accuracy of data from the RSE. As an outcome of the project team's technical assessment of this safety application, it is proposed to investigate GPS accuracy and lane-level road geometry in addition to the road geometry broadcast by the RSE. Human-Machine Interface (HMI) standards are continuously evolving and further work is needed to ensure the best result while maintaining OEM flexibility in implementation.

3.1.6 Spot Weather Information Warning

The objective of the Spot Weather Information Warning (SWIW) application is to provide a cooperative vehicle and infrastructure system that assists drivers in avoiding crashes in areas prone to adverse weather impacts by warning the vehicle driver that a crash-imminent situation is possible, particularly if precautions are not taken, such as reducing speed or seeking an alternate route.

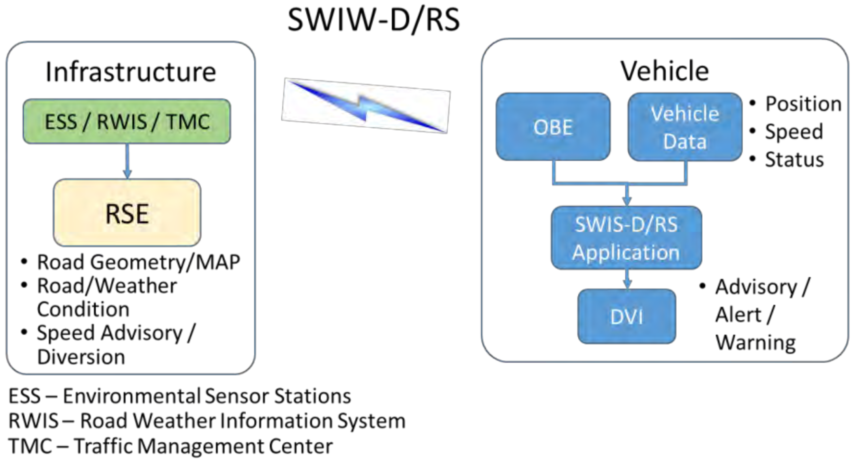
3.1.6.1 Functional Behavior

The infrastructure application component will collect available infrastructure and vehicle data, most importantly from the Road Weather Information System (RWIS) and process available data to recommend an appropriate advisory, alert, and/or warning message. Depending upon the availability of data for validation (e.g., redundant RWIS data source, traffic speeds), validation of the recommended message may be needed from a back-office Traffic Management Center (TMC) before the message is posted on the DII. An equipped vehicle approaching an RSE equipped roadway segment will receive a message that includes data regarding the message posted on the DII, length of adverse weather impact zone (throughout which the DVI message should apply), weather data collected by RWIS, and, if available, the advisory speed recommended and/or diversion to an alternate route as recommended by the infrastructure application component.

The application is separated into the two use cases, Diversion (SWIW-D) and Reduced Speed (SWIW-RS). In the former use case the infrastructure application component provides early information about a closed road ahead as well as a suggested detour. This information is then displayed to the driver who can take measures accordingly. In the latter use case, it is assumed that the road is not completely obstructed and that the driver can proceed with caution through the adverse weather or road condition. The driver is issued an advisory, alert and/or warning message if the vehicle processing platform determines that, given current operating conditions, an unsafe driving situation is likely to occur, and notifies the driver if reduced speed or an alternate route is recommended. The SWIW-D/RS application concept is illustrated in Figure 14. The information flow is shown in Figure 15.

Source: CAMP – V2I Consortium

Figure 14: SWIW-D/RS Concept Illustration



Source: CAMP – V2I Consortium

Figure 15: Information Flow for SWIW-D/RS

3.1.6.2 Technical Assessment of SWIW-D/RS

This subsection provides the technical assessment for the infrastructure and vehicle application components of SWIW-D/RS based on review of the application performance requirements [12] [13], system performance requirements [10] and application ConOps [11] documents.

On the infrastructure side, systems like the proposed system are already in place. It is technically feasible to locally detect bad weather conditions and display them to drivers using a DII. It should be noted that the application can only be deployed in locations where Environmental Sensor Data (ESD) is available.

This application provides the transmission of the collected data to approaching vehicles. Placement of DSRC equipment is crucial to a successful deployment of the application. For the RS use case a rather short distance (<500 m) between the receiving vehicle and the hazardous area might be appropriate as the vehicle only needs to slow down over that distance. In the case of alternative route being suggested, multiple RSEs or an RSE located at the diversion point should be used because DSRC range of 300 m from the location of road closure may not be adequate distance to provide an alternative route at appropriate timing. The correct RSE locations should be defined based on the location and the allowed speeds.

Based on the information received from the RSE, algorithms in the vehicle must determine if an advisory, alert or warning message is to be displayed. To properly assess this information, the pre-determined weather-impact threshold should be provided to OEMs/suppliers, or transmitted from the infrastructure RSE to the vehicles. The timing of alerts or warnings of the SWIW application should be common between the DII and DVI. In addition, the data elements describing the geometry of the area and the algorithms matching the vehicle to this area require further specification.

The specification indicates that the vehicle application component should determine the vehicles' dynamic capabilities to calculate speeds and distances at which alerts should be displayed. It has not yet been specified how this should be done and what the sensor requirements would be. The specification further states that default values should be used if specific values are not available. These calculations remain to be designed and evaluated.

3.2 Application Selection Criteria

This section describes the criteria developed to support selection of candidate V2I safety applications for build and evaluation. A representative cross section of the applications highlighted in the AASHTO National Connected Vehicle Field Infrastructure Footprint Analysis is recommended in order to explore vehicle-infrastructure interaction in a wide range of scenarios. The V2I safety applications identified by the AASHTO analysis are:

- SSGA
- RLVW
- CSW
- RSZW
- SWIW

These applications address intersections, vehicle speed and localized anomalies in traffic flow as shown in Table 3. Focusing on infrastructure interaction and deployment, and considering the cost and timing limitations of the current project, the project team selected a representative cross section of V2I safety applications. The project team elected to build one intersection-based, one speed-related and one spot-location warning application to explore the range of potential benefits associated with V2I communication-based safety.

Looking at the intersection applications identified it is clear from AASHTO's infrastructure deployment analysis that signalized intersections will provide a significantly greater number of installations over time in higher density environments, thereby justifying the selection of RLVW as a pilot intersection-based application. Considering localized variances in normal traffic flow, while weather related issues are certainly important, work zones appear to be an easier condition to replicate in order to explore this application category. Therefore, it is proposed to consider RSZW as a pilot spot-location application. The project team will also explore CSW as the speed-related application.

The rationale for the application selection and the selection criteria described in the following subsection were determined in cooperation with the FHWA.

Table 3: Criteria for Representative V2I Safety Application Build Selection

					Speed				
Application Grouping			Intersection			Traffic Anomalies			
Application Selection Criteria			Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning - *Reduced Speed*	Reduced Speed Zone Warning - *Lane Closure*	Spot Weather Information Warning- *Diversion*	Spot Weather Information Warning - *Reduced Speed*
V2I Development Attributes	1	Can this application also be realized with DSRC-based V2V Communication? (Y/N)	Yes	No	No	No	No	No	Yes
V2I Development Attributes	2	Can this application provide additional benefits in the vehicle beyond what can be provided by the infrastructure alone? (Low, Med, High)	Low	High	High	Med	High	Med	High
V2I Development Attributes	3	Potential for conflict between DII and DVI to increase false positives (Low, Med, High)	Med	Med	Low	Low	Med	Low	Low
V2I Development Attributes	4	Is this application scalable and can it be easily implemented at different locations? (Y/N)	Yes	Yes (w/ adjustments)	Yes	Yes	Yes	Yes	Yes
V2I Development Attributes	5	Is this application identified as a high potential safety application? (Y/N)	Yes	Yes	Yes	No	No	No	No
V2I Development Attributes	6	Application extensibility for infrastructure RSE (Low, Med, High)	Low	High	Med	Med	Low	Med	Med
V2I Development Attributes	7	Roadside infrastructure upgrade costs (Low, Med, High)	High	Low	Low-Med	Low-Med	Low-Med	Low-Med	Low-Med
V2I Development Attributes	8	Backend server support (Necessary / Preferred / Not Necessary)	Not Necessary	Preferred	Preferred	Preferred	Preferred	Necessary	Necessary
V2I Development Attributes	9	Equipment setup, operations and maintenance cost (Low, Med, High)	High	Med	Low	Med	Med	Low-Med	Low-Med
Project Impact	10	Development & Testing effort for the vehicle application component (Low, Med, High)	Low	Med	Low-Med	Low	Low-Med	Low	Low
Project Impact	11	Development & Testing effort for the infrastructure application component (Low, Med, High)	High	Low-Med	Med	Low-Med	Med	Low-Med	Low-Med
Project Impact	12	Positional (vehicle) and map data requirements (Low, Med, High)	Med	High	Med	Low	High	Low	Low
Representative Application Build Selection				✔	✔	✔			

Source: CAMP – V2I Consortium

3.2.1 Description of Selection Criteria

The project team defined the criteria for selecting the prototype applications to be developed and evaluated. The criteria outlined in Table 3 are categorized as: 1) V2I Deployment Attributes and 2) Project Impact.

3.2.1.1 V2I-SA Deployment Attributes

1. Can this application also be realized with DSRC-based V2V Communication? (Yes/No)

The project team used this criterion to investigate the possibility of also implementing an application using DSRC-based vehicle-to-vehicle (V2V) communication. In this case, an infrastructure component may not be required, though high penetration of V2V-communication equipped vehicles is required for the application to be beneficial.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Yes	No	No	No	No	No	Yes

SSGA: Yes. This application provides the lowest level of infrastructure benefit. V2I implementation may not be necessary in an environment with a high V2V DSRC penetration rate.

RLVW: No. This application is based on the information it receives from infrastructure (SPaT and MAP). There is no input coming from other vehicles that can be used to substitute the infrastructure information.

CSW: No. This information is not provided by V2V communication.

RSZW-RS: No. This application requires the infrastructure to provide certain information to the vehicle. This information is not provided by V2V communication. E.g., the latitude/longitude/ elevation of the beginning and ending locations of the reduced speed zone area, and other information such as the reduced speed value.

RSZW-LC: No. This application requires that the infrastructure provide certain information to the vehicle. This information is not provided by V2V communication. An example of such information is the work zone geometry including closed lane information and other information such as the reduced speed value.

SWIW-D: No. The Diversion (-D) use case requires knowledge about possible alternate routes in the area and the transmission of the messages should take place far in advance of the driver reaching the location where bad weather is reported. Depending on the location it may not be possible to realize this with direct V2V DSRC communication, thereby making V2I communication necessary.

SWIW-RS: Yes. The first of these criteria is the possibility to realize the application with V2V communication alone. For the Reduced Speed (-RS) use case the necessary information could be provided by data elements and messages defined in SAE J2735.

2. ***Can this application provide additional benefits in the vehicle beyond what can be provided by the infrastructure alone? (Low, Med, High)***

The project team used this criterion to evaluate the additional benefits provided by a vehicle application component beyond what can be provided by a stand-alone infrastructure application. Additional vehicle parameters (e.g., wiper status, outside ambient temperature) can be used in the algorithm to provide better and more relevant information to the driver.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Low	High	High	Med	High	Med	High

SSGA: Low. This application could be implemented with infrastructure only, as a basic application.

RLVW: High. This application helps drivers caught in a dilemma zone and in cases where the traffic light is not visible to the driver (e.g., obstructed by environment, full sunlight, high semi-trailers).

CSW: High. This application is very useful in the event the driver is not expecting a curve in the road and is driving too fast to negotiate the curve, as well as in inclement weather conditions. Vehicle-embedded warnings may be effective to alert driver in various weather/road conditions compared to warnings displayed solely on the infrastructure. This application is especially useful if an upcoming curve is obscured by weather conditions (e.g., fog).

RSZW-RS: Med. An in-vehicle warning may be more effective to alert a distracted driver compared to an external visual warning displayed on the DII.

RSZW-LC: High. This application provides vehicle-specific DVI alert and warning messages in the case of lane closure conditions.

SWIW-RS: High. The application enables the vehicle to perform additional calculations based on its capabilities and current dynamics. This information has potential to provide greater accuracy for warnings and may add more value than as just a display device.

SWIW-D: Med. With this application the vehicle will likely not obtain additional information or do extensive additional calculations. It will display the information provided by the infrastructure to the driver.

3. Potential for conflict between DII and DVI to increase false positives (Low, Med, High)

The project team used this criterion to evaluate the potential for conflict between DII and DVI to generate false positives. For example, in RLVW, an intersection that does not have dedicated right turn lane and associated SPaT information may produce a false positive if the driver turns right on red where permitted. In such cases, the application may infer the driver intent based on vehicle status such as a turn signal indicator. However, if the turn signal indicator is not activated, a false positive (i.e., warning) could be generated.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Med	**Med**	**Low**	**Low**	**Med**	**Low**	**Low**

SSGA: Med. This application can be implemented at different levels (described in Section 3.1.2). Depending on the level of implementation, it is likely that the information provided to the DII by the infrastructure application component and to the DVI by the vehicle application component may represent conflicting information.

RLVW: Med. This application requires lane-level position accuracy to avoid generating a false warning to the driver. It is likely that if this level of positioning accuracy is not available at intersections with a dedicated turn lane or where a turn on red is permitted, the application may generate a false warning to the driver.

CSW: Low. While this application may benefit from lane-level position determination it is not required.

RSZW-RS: Low. The application requires the road-level position accuracy, which is achievable with current GPS systems.

RSZW-LC: Med. This application requires lane-level positioning. If this is accuracy is not available the application may generate false warnings.

SWIW-D, SWIW-RS: Low. This application relies mainly on road and weather condition information from the infrastructure (e.g., weather service, road condition sensor).

4. Is this application scalable and can it be easily implemented at different locations? (Yes/No)

The project team used this criterion to evaluate whether an application can be easily replicated in a different location simply by updating the map data for the new location.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Yes	**Yes** (w/ adjustments)	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

All Applications: Yes. Nearly all the applications can be easily implemented to support different locations. However, RLVW may require an adjustment to the algorithm to support specific local or regional requirements or highly complex intersections.

5. Is this application identified as a high potential safety application? (Yes/No)

The project team used this criterion to evaluate whether an application has been identified by the FHWA as a high potential safety application.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Yes	**Yes**	**Yes**	**No**	**No**	**No**	**No**

SSGA, RLVW and CSW: Yes. These applications were selected for accelerated application based on their potential to produce safety benefits [4] [5].

RSZW-RS, RSZW-LC, SWIW-D, and SWIW-RS: No. These applications are not identified as accelerated applications. They are, however, considered for deployment based on their potential benefits, readiness of technology and needs expressed by stakeholders.

6. Application extensibility for infrastructure RSE (Low, Med, High)

The project team used this criterion to evaluate whether the extensibility of an application allows flexibility to quickly generate another V2I application that is similar in nature. For example, a RSZW application can be quickly modified and extended to support a "low clearance" advisory.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Low	**High**	**Med**	**Med**	**Low**	**Med**	**Med**

SSGA: Low. This application does not have technical similarities to other applications. The infrastructure put in place for this application cannot accommodate other applications being developed in this project.

RLVW: High. The infrastructure put in place for this application can accommodate other V2I projects being developed under other CAMP projects such as Applications for the Environment: Real-time Information Synthesis (AERIS).

CSW: Med. This application is similar technically to RSZW and SWIW-RS with minor application modification.

RSZW-RS: Med. The functionality of this application is very similar to CSW and SWIW-RS. With some modifications this application could work as CSW or SWIW-RS

RSZW-LC: Low. The functionality of this application requires lane-level positioning accuracy and map data, limiting the application's extensibility for other uses.

SWIW-D and SWIW-RS: Med. The fact that either application will only be deployed in specific locations results in a medium potential for extensibility. For example, in cases where bad weather conditions could occur on or near a curve, the application could be combined with the CSW application.

7. Roadside infrastructure upgrade costs (Low, Med, High)

The project team used this criterion to evaluate the cost of upgrading roadside infrastructure (e.g., required electrical power source, underground cabling installation) to support the application. For example, installing SSGA in rural areas requires installing sensors in both directions along the major roadway to detect and measure the speed of the vehicles, an RSE to broadcast the information to the equipped vehicles along the minor roadways, and power, associated cabling and equipment mounting for both.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
High	**Low**	**Low-Med**	**Low-Med**	**Low-Med**	**Low-Med**	**Low-Med**

SSGA: High. Multiple infrastructure components (e.g., radar sensors to detect and measure speed of vehicles on major roadway, an RSE, power, DII) are required for this application.

RLVW: Low. An RSE interfaced with the signal light controller is required for the application.

CSW, RSZW-RS, RSZW-LC, SWIW-D, SWIW-RS: Low-Med. These applications may require low to medium level of cost to upgrade the infrastructure since many locations may not have electrical power required to support them. The cost could be low for portable systems.

8. Backend server support (Necessary / Preferred / Not Necessary)

The project team used this criterion to evaluate the level of support required from a backend server for the application to provide the most benefit. For example, in the case of the SWIW application, detection of road and weather conditions would require backend server support for the vehicle application component to provide any desired advisory/warning to the driver.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Not Necessary	**Preferred**	**Preferred**	**Preferred**	**Preferred**	**Necessary**	**Necessary**

SSGA: Not Necessary. This application does not require backend server support nor is information from the backend necessary to support the application.

RLVW, CSW, RSZW-RS, and RSZW-LC: Preferred. These four applications can benefit from having additional information provided by the backend server e.g., GPS corrections, road and weather conditions, SPaT and MAP (for RLVW).

SWIW-D and SWIW-RS: Necessary. These two applications require weather and road condition information for the vehicle application component to be effective.

9. Infrastructure equipment setup, operations and maintenance costs (Low, Med, High)

The project team used this criterion to evaluate the costs of setting up, operating and maintaining the required infrastructure to support the application. For example, in the case of SSGA, in addition to the cost of installing sensors and an RSE in rural areas, the cost of maintaining the roadside sensors for proper calibration and the surrounding environment are considered.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
High	**Med**	**Low**	**Med**	**Med**	**Low-Med**	**Low-Med**

SSGA: High. In this application installing and calibrating roadside radar sensors to detect vehicles and speeds on the major roadway could be more costly than other applications. Additionally, the cost of maintaining the roadside sensors and the surrounding environment could add to the cost of maintaining the site.

RLVW, RSZW-RS, RSZW-LC: Med. These applications would require a medium level of effort to setup and operate the infrastructure. Additionally, in the case of RLVW and RSZW-LC, local GPS corrections would be required to support lane-level position accuracy. Additional efforts are needed for RSZW-RS/LC for work zones to develop lane-level Map data.

CSW: Low. For a fixed RSE unit, the cost is considered to be low.

SWIW-D/RS: Low-Med. Both applications would require low to medium level costs to maintain for portable units. For fixed units, the cost could be low.

3.2.1.2 Project Impact

10. Development & Testing effort for the vehicle application component (Low, Med, High)

The project team used this criterion to evaluate the time to develop and test the vehicle application component as a portion of the time and resource levels available in the project plan.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Low	Med	Low-Med	Low	Low-Med	Low	Low

SSGA, RSZW-RS, SWIW-D, and SWIW-RS: Low. Time to develop and test these vehicle application components in vehicle is low compared to the other applications. These applications do not require lane-level map and GPS accuracy, thereby requiring less time for development and testing.

CSW, RSZW-LC: Low-Med. These applications are estimated to take low to medium levels of effort to develop and test. For example, to determine lane position in the case of RSZW-LC and to determine vehicle dynamics and stability on the curve in the case of CSW sufficiently to allow for proper warning to the driver would require a medium level of effort.

RLVW: Med. This application is estimated to take a medium level of effort to develop and test. For example, to address intersection variations (e.g., dedicated turn lane versus no dedicated turn lane, no turn on red) could require a medium level of effort to develop and test the application.

11. Development & Testing effort for the infrastructure application component (Low, Med, High)

The project team used this criterion to evaluate the time to develop and test the infrastructure application component as a portion of the time and resource levels available in the project plan.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
High	Low-Med	Med	Low-Med	Med	Low-Med	Low-Med

SSGA: High. This application would require high amounts of effort to develop and test various options as it needs additional infrastructure setup for detecting vehicles and determining their speed on the major roadway to provide appropriate information to the driver on the minor roadway.

CSW, RSZW-RS, SWIW-D, and SWIW-RS: Low-Med. These three applications would require low to medium amounts of effort during development and testing compared to the SSGA application.

CSW and RSZW-LC: Med. These three applications would require a medium level of effort to develop and test the infrastructure application component.

12. Positional (vehicle) and map data requirements (Low, Med, High)

The project team used this criterion to evaluate the application requirement for lane-level map data and the need for GPS corrections for the application to function as desired and produce minimal false positives.

Stop Sign Gap Assist	Red Light Violation Warning	Curve Speed Warning	Reduced Speed Zone Warning-RS	Reduced Speed Zone Warning-LC	Spot Weather Information Warning-D	Spot Weather Information Warning-RS
Med	High	Low	Low	High	Low	Low

SSGA: Med. This application requires mainly road-level position accuracy for the vehicle, however, MAP data for an intersection with multiple lanes on a major roadway and the approach road (lane) leading to the intersection may be complex in nature.

RLVW, RSZW-LC: High. These two applications require lane-level position accuracy to properly determine the vehicle position on a specific lane to generate appropriate information for the driver.

CSW, RSZW-RS, SWIW-D, and SWIW-RS: Low. These applications require only road-level vehicle position accuracy to function and to provide benefits. These can be achieved with currently used GPS sensors and do not require GPS corrections.

3.3 Application Selection

Various deployment attributes and project impact factors were assessed for each of the five safety applications. The selection criteria also leveraged the National Connected Vehicle Field Infrastructure Footprint Analysis conducted by AASHTO [1] as well as inputs from the FHWA project staff. The findings formed the basis for the project team's selection of a representative subset of applications.

Three applications (RLVW, CSW and RSZW-LC/RS) addressing intersections, vehicle speed, and localized traffic variances were selected as pilot applications for further investigation.

4 Application Development Plan

This section describes the work plan prepared prior to initiating the work to develop and evaluate the three prototype V2I safety applications selected for further development in the project. The application selection was described in Chapter 3. The plan established the timeline, milestones, deliverables and allocation of responsibilities across V2I Consortium Participants and contracted suppliers. All development activities up to the beginning of field testing were included in the work plan. The work plan was reviewed with FHWA prior to commencing the development work. The work plan is summarized below.

4.1 Safety Applications and OEM Participation

The V2I safety applications that were evaluated in this project were developed to a prototype level to evaluate functionality and verify interoperability with deployed infrastructure and standards. Vehicles were operated by participating OEM employees; they were not intended for use by the general public.

4.1.1 Safety Applications

Three prototype applications addressing intersections, vehicle speed, and localized traffic variances were developed for evaluation.

- Red Light Violation Warning (RLVW)
- Curve Speed Warning (CSW)
- Reduced Speed Zone Warning (RSZW)
  - Reduced Speed in a work or school zone
  - Lane Closure(s) in a work zone

4.1.2 OEM Participation

V2I Consortium member OEM participation is grouped in three categories.

- Leaders integrated all selected applications in their vehicles for testing and evaluation; leaders also played a significant role in application development and testing, and coordination with infrastructure providers
- Evaluators contributed to application design, implemented the application software and performed testing
- Observers contributed to application design and other aspects of the project and observed development and testing

Table 4 lists the participating OEMs, their roles in the project, and the vehicle make and model identified by each for implementing the applications.

Table 4: List of Participating OEMs for Safety Applications

V2I Safety Applications						
V2I Member Company	Vehicle Make & Model	RLVW	CSW	RSZW-*Reduced Speed*	RSZW-*Lane Closure*	Role of Participant
FCA	-					Observer
Ford	-					Observer
GM	Buick LaCrosse	√	√	√	√	Evaluator
Honda	2014 Acura RLX	√	√	√	√	Evaluator
Hyundai-Kia	Kia K-900	√	√	√	√	Leader
Mercedes Benz	-					Observer
Mazda	-					Observer
Nissan	2011 Infiniti M37	√	√	√	√	Evaluator
Subaru	Subaru Legacy	√	√	√	√	Evaluator
Volvo Truck	VNL 670s Truck	√	√	√	√	Evaluator
VW/Audi	Audi A4	√	√	√	√	Leader

Source: CAMP – V2I Consortium

4.2 Selection of Test Locations

In this section, potential locations are identified for application test and evaluation. During the project, different locations were necessary to both exercise the full range of application functionality and evaluate interoperability with deployed infrastructure. For example, full CSW and RSZW application testing required vehicle speeds above posted limits; RLVW required a red light violation to validate its correct operation. While preliminary communications testing can be performed in a static environment, dynamic testing and validation of full application functionality was conducted at closed-course test facilities. Final testing and evaluations performed on public roads showed vehicle / infrastructure application component interoperability during normal operation.

4.2.1 Red Light Violation Warning

For the RLVW safety application, consideration was given to two types of signalized intersections: a simple intersection without protected or dedicated lanes for left or right turns and a complex intersection with protected or dedicated left or right turns where the turn phase differs from the straight crossing phase. Additional consideration was given to intersections that are supported under the United State Department of Transportation (USDOT) Connected Vehicle Reference Implementation Architecture (CVRIA) South Eastern Michigan (SEMI) Test Bed. The two selected intersections were: Telegraph Road and W. 12 Mile Road, and Telegraph Road and W. 10 Mile Road in Southfield, Michigan. These selections represent intersections of medium complexity, where an ingress road is composed of three lanes with the following permitted maneuvers:

- One lane dedicated for the right turn only maneuver, with right turn on red only permitted during specific hours of the day
- One lane with right turn and straight crossing maneuvers permitted
- One lane with straight crossing only maneuver

- No direct left turns are permitted at these intersections. Left turns require the driver to first execute a right turn then execute a U-turn

The selected intersections were capable of transmitting SPaT and intersection MAP messages defined in SAE J2735 standard. Consequently, the prototype safety application can be evaluated in a real driving environment. Figure 16 shows a Google aerial view of the first intersection, at Telegraph Road and W. 12 Mile Road.

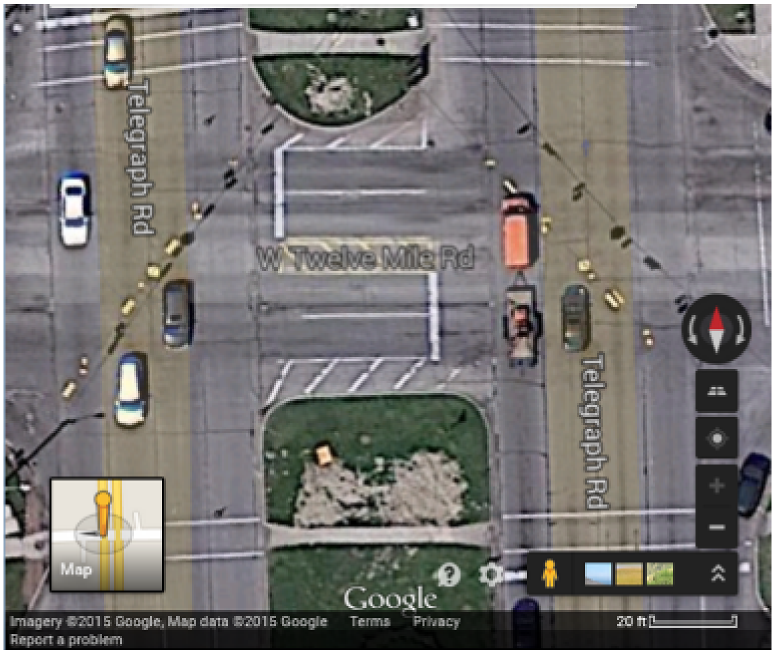


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Figure 16: Aerial View of Telegraph Road and W. 12 Mile Road, Southfield, Michigan

Figure 17 shows a street level view of the intersection, facing east on W. 12 Mile Road at Telegraph Road.

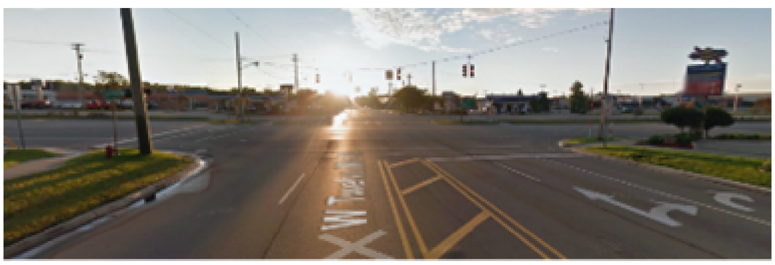

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Figure 17: Street View of W. 12 Mile Road at Telegraph Road, Southfield, Michigan

Figure 18 shows a Google aerial view of the second intersection, at Telegraph Road and W. 10 Mile Road.

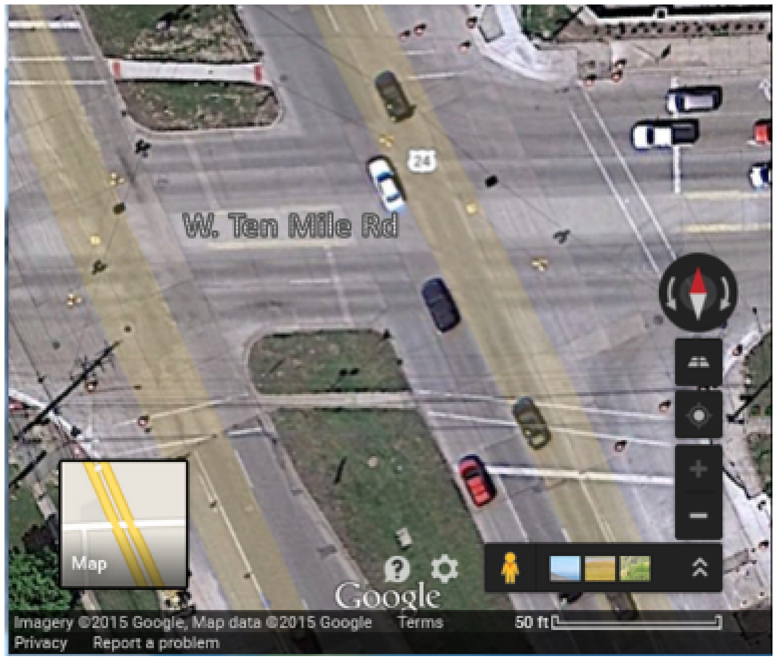

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Figure 18: Aerial View of Telegraph Road and W. 10 Mile Road, Southfield, Michigan

Figure 19 shows a street level view of the intersection, facing north on Telegraph Road at W. 10 Mile Road.

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Figure 19: Street View of Telegraph Road at W. 10 Mile Road, Southfield, Michigan

Table 5 provides a description of the RLVW test sites, associated web links and relevant attributes of the signalized intersections.

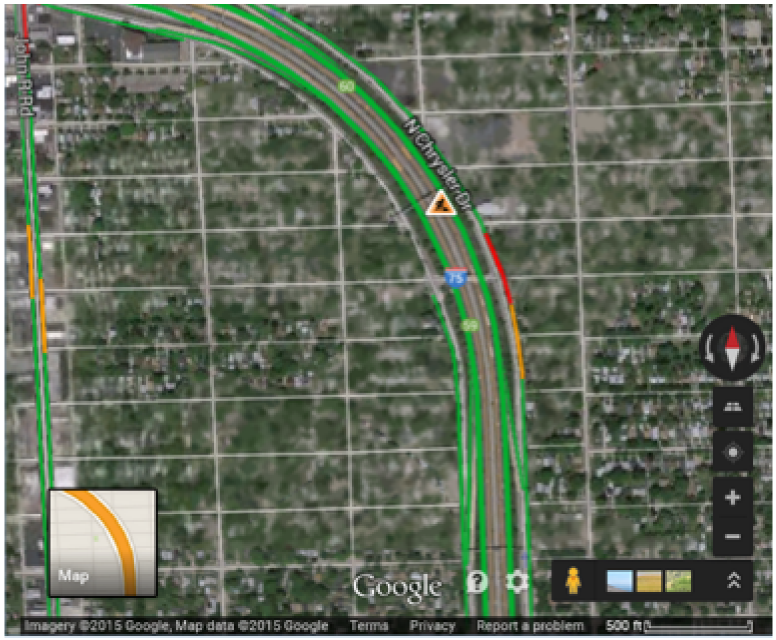
Table 5: Test Sites for RLVW Application

Safety Application	Test Location	Link	Test Location Attributes
RLVW	Telegraph Road & W. 12 Mile Road, Southfield, Mich. Telegraph Road & W. 10 Mile Road, Southfield, Mich.	https://www.google.com/maps/@42.5009191,-83.2856692,19z https://www.google.com/maps/@42.4719342,-83.2814253,122m/data=!3m1!1e3	USDOT CVRIA SEMI Test Bed location 3 Lanes for ingress 1 Dedicated lane for right turn Right turn on red is permitted during specific hours of the day 1 Lane for straight across and right turn 1 Lane for straight across only No direct left turns are permitted. Left turns require first to execute a right turn then a U-turn

Source: CAMP – V2I Consortium

4.2.2 Curve Speed Warning

The first site selected for CSW is located on interstate I-75 south of 9 Mile Road in Hazel Park, Michigan. Figure 20 shows a Google aerial view of the location. This site was considered based on MDOT's suggestion because historically the location exhibits a high incidence of crashes. The curve at this site has a posted speed limit of 70 mph with a 55 mph speed advisory in the curve.



Source: © 2015 Google, Inc. Used with Permission

Figure 20: Aerial View of Interstate 75 South of 9 Mile Road, Hazel Park, Michigan

The second test site selected for CSW is the freeway interchange between I-94 and M-10 in Detroit. Figure 21 shows a Google aerial view of the location. This site was also suggested by MDOT because of the high incidence of crashes. The freeway speed limit is 55 mph and the advisory speed in the curve is 40 mph.

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Figure 21: Aerial View of I-94 and M-10 Freeway Interchange, Detroit, Michigan

Table 6 provides a description of the CSW test sites, associated web links and relevant attributes of the test sites.

Table 6: Test Sites for CSW Application

Safety Application	Test Location	Link	Test Location Attributes
CSW	Interstate I-75, South of the 9 Mile Road Exit, Hazel Park, Mich.	https://www.google.com/maps/@42.4567191,-83.0989095,1308m/data=!3m1!1e3!5m1!1e1	Suggested by MDOT due to high crash incidence history Speed limit of 70 mph Curve advisory speed of 55 mph
	Interchange between I-94 and M-10 freeways, Detroit, Mich.	https://www.google.com/maps/@42.3590095,-83.0762809,164m/data=!3m1!1e3!5m1!1e1	Suggested by MDOT due to high crash incidence history Speed limit of 55 mph Curve advisory speed of 40 mph

Source: CAMP – V2I Consortium

4.2.3 Reduced Speed Zone Warning

The RSZW application consists of two use cases. The first use case is Reduced Speed in a work zone or school zone. The second use case is Lane Closure(s) in a work zone. The following three options were considered for testing the application:

1. Reduced speed advisory in a work / school zone
2. Reduced speed and a lane closure advisory in a work zone
3. Reduced speed and a lane closure advisory and warning in a work zone

To conduct basic reduced speed advisory tests for Option 1, Hills Tech Drive at Haggerty Road near the CAMP facility in Farmington Hills, Michigan was identified. Hills Tech Drive represents a wide road with light traffic for simulating the reduced speed advisory. It also provides accessibility to an adjacent vehicle parking area where an RSE can be placed for testing. Figure 22 shows a Google aerial view of the test location and Figure 23 shows a street view of the Hills Tech drive from Haggerty Road facing east.

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Figure 22: Aerial View of Hills Tech Drive at Haggerty Road, Farmington Hills, Michigan

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Figure 23: Street View of Hills Tech Drive from Haggerty Road, Facing East

To conduct lane closure testing for Option 2, a test site with an actual physical lane closure was preferred. The closure could be the result of a work zone or a site with a permanent lane closure. However, many work zones are temporary and the presence of work crews may be transient. Thus, a site with a permanent lane closure is a better selection. Figure 24 depicts a street level view of a permanent lane closure on Farmington Road at W. 13 Mile Road in the Farmington Hills area where a permanent lane closure exists.

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Source: © 2015 Google, Inc. Used with Permission

Figure 24: Street View of Farmington Road at W. 13 Mile Road with Lane Closure

To conduct Option 3 tests combining both reduced speed and lane closure in a controlled and sustainable manner, a closed test track was used to simulate a work zone scenario with lane closure using safety cones.

Table 7 provides a description of the test sites for RSZW for all three options, associated web links and relevant attributes of the test sites.

Table 7: Test Sites for RSZW Application

Safety Application	Test Location	Link	Test Location Attributes
RSZW	Option 1 - Reduced Speed Advisor Hills Tech. Drive off Haggerty Road, Farmington Hills, MI	https://www.google.com/maps/place/Hills+Tech+Dr,+Farmington+Hills,+MI+48331/@42.4897662,-83.4350896,164m/data=!3m1!1e3!4m2!3m1!1s0x8824afd98d1ec65f:0x689b951310451a0d	Wide road, light traffic Near CAMP facility Reduced speed advisory option test location RSE placement available for test
	Option 2 - Lane Closure Advisory Farmington Road & W. 13 Mile Road, Farmington Hills, MI	https://www.google.com/maps/@42.5139352,-83.3789704,491a,20y,90h/data=!3m1!1e3?hl=en	Permanent lane closure Near CAMP facility Lane closure advisory option test location RSE placement available for test
	Option 3 - Reduced Speed and Lane Closure Advisory & Warning Closed Test Track		Simulated work zone environment with lane closure

Source: CAMP – V2I Consortium

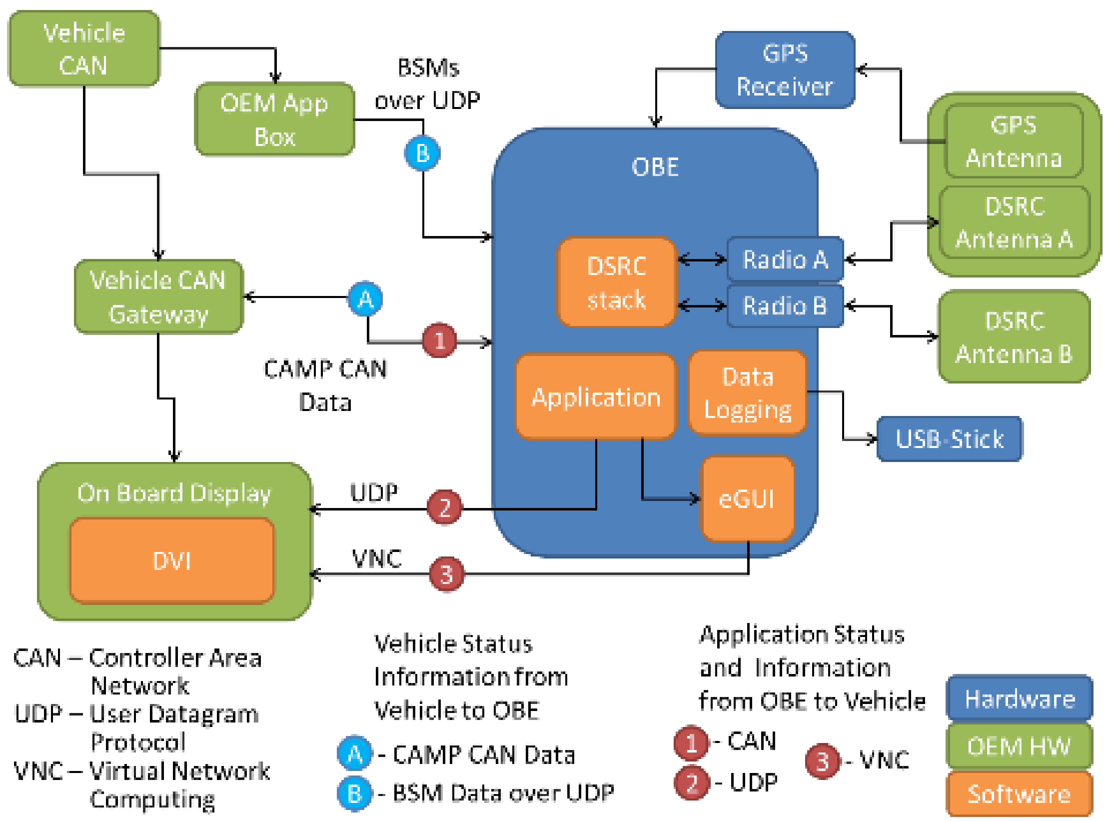
4.3 Vehicle Integration

The vehicle side of the V2I safety applications were developed as common components for all the participating OEMs. The outline of the in-vehicle architecture and the interfaces for integration with the OEM specific components are described in the following subsections.

4.3.1 Vehicle Architecture

Figure 25Source: CAMP – V2I Consortium

Figure 25 shows the current working draft of the in-vehicle architecture with its hardware and software components. The architecture may be revised going forward based on the selected supplier's component hardware requirements.



Source: CAMP – V2I Consortium

Figure 25: Safety Application In-Vehicle Architecture

In general, the project team plans integrated a common OBE with all three applications developed jointly with the supplier into the test vehicles. The unit included DSRC radios and a GPS receiver. The OBE included the DSRC software stack and a data logging system to collect predefined relevant data during the development and testing of the application. Furthermore, the developed applications and an Engineering Graphical User Interface (eGUI) were also implemented and executed on the OBE. The eGUI was used for development purposes to display debugging parameters in addition to advisory and warning messages.

Each OEM integrating the safety applications into their vehicle was responsible for providing vehicle status data to the OBE for use by the application algorithm either using the CAMP Controller Area Network (CAN) connection or by providing BSM data over the User Datagram Protocol (UDP) connection as indicted in in Figure 25 and for providing the OEM-specific DVI.

4.3.2 Vehicle Data

The safety applications used vehicle status data, which was typically transmitted on the CAN bus. To reduce the implementation effort and not to require the OEMs to disclose their proprietary CAN message formats, each OEM participant translated their internal CAN data to a common CAN message format developed by CAMP. The OBE will receive CAN frames encoded using this common format. Thus, the application did not need to know in which vehicle it is operating.

4.3.3 Driver-Vehicle Interface

Each of the three safety applications issued advisory and warning messages through the generic eGUI to streamline development time. Because there were no plans to connect a display directly to an OBE, the display data for the eGUI could be accessed using the Virtual Network Computing (VNC) protocol and displayed on an OEM-provided display (shown as connection '3' in Figure 25). In addition, individual OEM participants developed their own DVI solution for the safety applications. For this purpose, a CAN message ('1') as well as an UDP protocol ('2') will be developed to communicate the status and information from various applications to the OEM DVI.

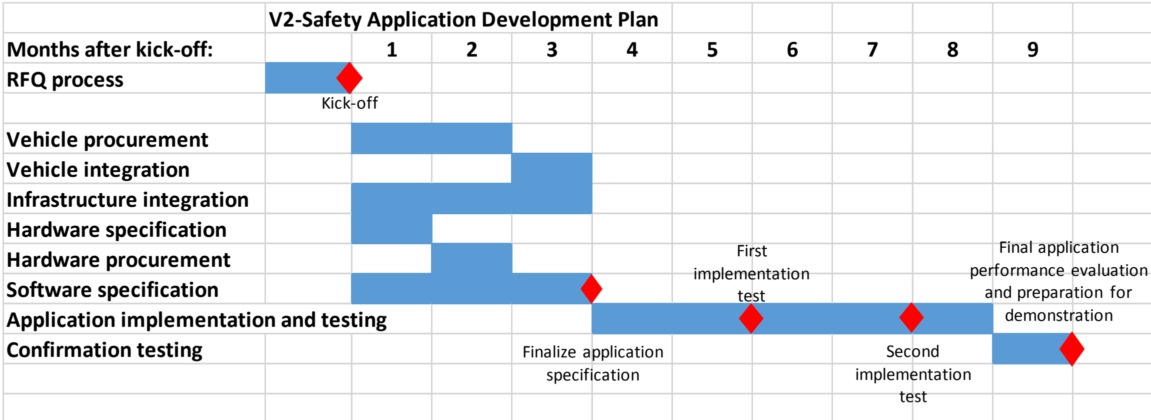
4.4 Application Development and Test Plan

Table 8 presents a summary of the application development and test plan. Figure 26 shows the timeline for application development and implementation testing. Development and testing were expected take up to nine months to complete.

Table 8: Safety Application Development and Test Plan

Activity	Supplier	CAMP	Date
Kickoff meeting	Support	Lead	Beginning of M1
Finalize CAN Catalogue / Message definitions		Lead	End of M1
Conduct application test workshops	Lead	Support	M2 to end of M8
Provide OBE hardware including connectors	Lead		End of M2
Complete in-vehicle integration of OBE	Support	Lead	End of M3
Finalize application specifications	Support	Lead	End of M3
Infrastructure Architecture Build (Infrastructure integration)	Lead		End of M3
Application Software - First implementation testing	Lead		End of M5
Complete Objective Test Procedures (OTP)	Support	Lead	End of M5
Application Software – Second implementation testing	Lead		End of M7
Complete evaluation of final application performance and prepare for testing and evaluation	Support	Lead	M9
Convene regular weekly meeting	Support	Lead	Throughout the project
Conduct maintenance of open items list	Support	Lead	Throughout the project

Source: CAMP – V2I Consortium



Source: CAMP – V2I Consortium

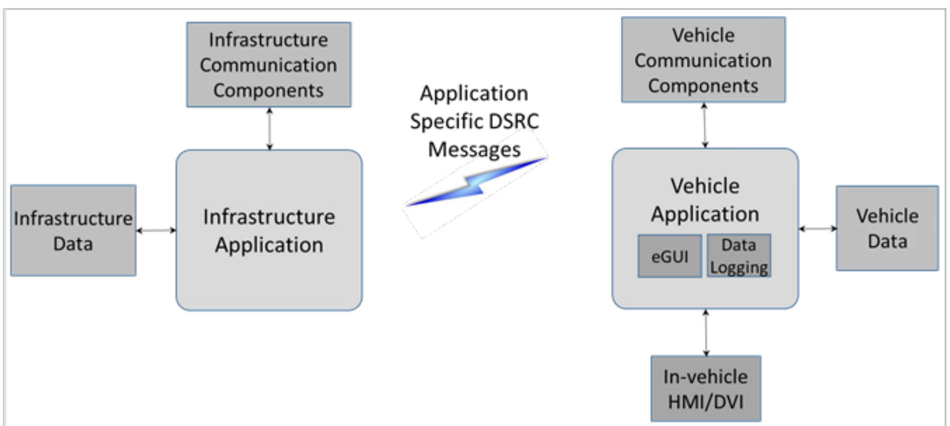
Figure 26: Safety Application Development and Testing Timeline

5 Safety Applications – System Architecture

A system architecture for the V2I safety applications that were designed and developed as a part of this project is described in this chapter. At a high level, the system architecture can be classified into vehicle- and infrastructure-based subsystems (i.e., physical components and application platform), and application-specific DSRC-based wireless messages as shown in Figure 27.

The RSE within the infrastructure-based subsystem broadcasted application specific infrastructure data such as signal phase and timing, road works data such as work zone/lane closure information, and road conditions for use by the applications.

The OBE within the vehicle-based subsystem received OTA DSRC messages from the infrastructure, and captured vehicle position information from a GPS receiver and vehicle status data through an interface such as CAN for use by applications. It also provided an interface to the DVI.



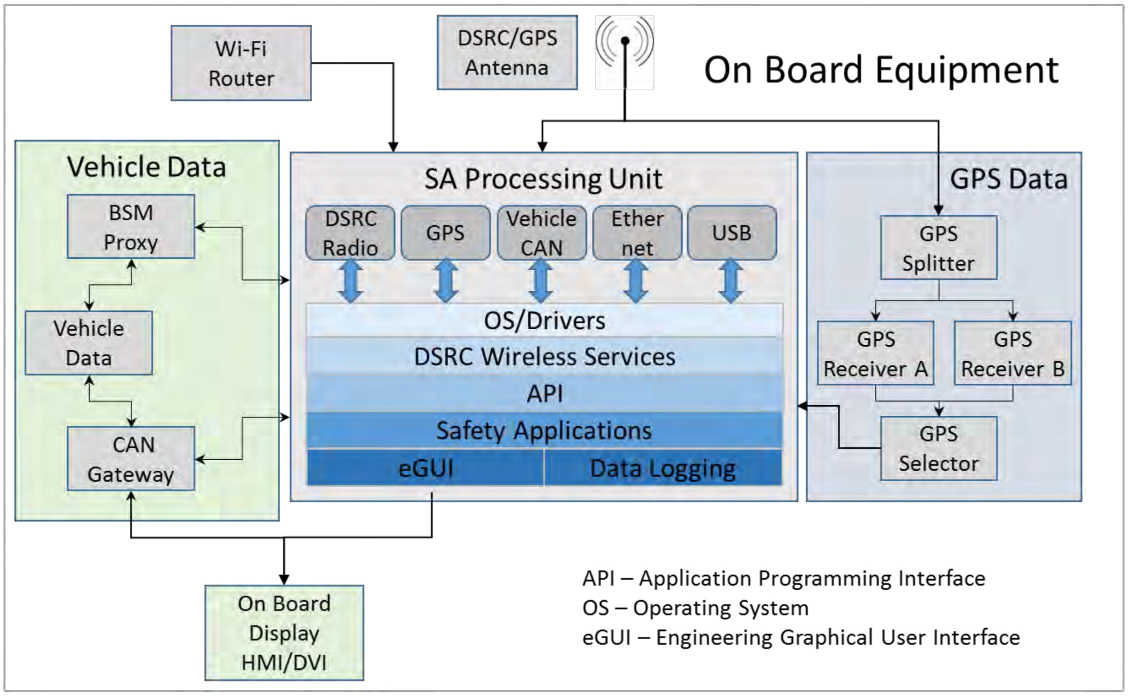
Source: CAMP – V2I Consortium

Figure 27: High-Level System Architecture for DSRC-based V2I Safety Applications

During application development, different concepts for transmitting relevant event information from the infrastructure to the vehicles were carefully evaluated. It was determined that the existing SAE J2735 DSRC messages are not adequate to support the CSW and RSZW/LC applications. This observation has motivated the design of the BIM based on the existing DSRC communication standard to support the applications. The BIM is discussed in Section 5.3.2.

5.1 In-Vehicle Architecture

Figure 28 shows a block diagram of the in-vehicle system architecture. A common OBE to support all three safety applications was developed with the assistance of an automotive supplier and integrated with the OEM test vehicles. The OBE consisted of a DSRC unit, a vehicle data subsystem, a GPS data subsystem, a display for DVI, and a wireless fidelity (Wi-Fi) router.



Source: CAMP – V2I Consortium

Figure 28: In-Vehicle Architecture Block Diagram

The Safety Applications Processing (SAP) unit consisted of a dual radio unit for DSRC communication, a GPS receiver for vehicle position, CAN interface for vehicle data, an Ethernet interface for communication with external devices, and a Universal Serial Bus (USB) interface for data logging. It included an Operating System (OS), software drivers, wireless services, and a software stack to run the developed applications. The eGUI enabled a visual display for debugging parameters in addition to the Inform / Warning 1 / Warning 2 messages as produced by the application algorithm. The eGUI was not intended for a production implementation. Data logging capability provided verbose logging of the data in the SAP unit for further analysis and replaying the test scenario. It also provided the interface for a DVI to display application-relevant information such as the Inform / Warning 1 / Warning 2 messages. The Wi-Fi router provided remote access to the SAP unit for software updates and downloading logged data. The vehicle data block highlighted in light green provided vehicle status data to the SAP unit for use by the application. OEM proprietary vehicle CAN data was translated by the CAN Gateway module into common CAMP CAN format developed for the project. The data was provided either in a common CAMP CAN format or as a BSM proxy message as designed in the OEM test vehicle. Each OEM integrating the safety applications into their vehicle was responsible for providing vehicle status data to the SAP unit for use by the application algorithm.

The GPS data subsystem consisted of two GPS receivers: 1) an automotive-grade receiver A that does not support RTCM correction and 2) a second receiver B for supporting RTCM correction as shown in Figure 28. A user selectable switch provided input to the SAP unit for the selected GPS receiver. This provided the capability to input GPS data with or without RTCM correction to the application algorithm for performance evaluations.

The in-vehicle application software resided on the SAP unit. The vehicle data was communicated with the SAP unit in one of two ways: 1) via CAN bus using a pre-defined CAMP CAN message structure or 2) as a BSM via Ethernet over User Datagram Protocol (UDP; i.e., BSM proxy).

The application output messages from the DSRC unit could be displayed on the vehicle DVI either through CAN or the Ethernet. The eGUI could be accessed using the Virtual Network Computing (VNC) server.

5.1.1 Vehicle Data Interface

This section describes the interface between the vehicle CAN gateway and the SAP unit. All CAN message data followed the 'Big Endian' data format and was transmitted on a high-speed CAN bus (500 kbps) at a frequency of 10 Hz. The CAMP CAN message structure has been implemented to provide common vehicle CAN data format to the SAP unit for application use. The following vehicle data elements are used by the application:

- Vehicle speed
- Driver intended braking
- Longitudinal and lateral acceleration
- Steering wheel angle and yaw rate
- Turn signal status

Two key conventions have been used:

- For the parameters, 'Steering Wheel Angle' and 'Yaw Rate,' clockwise was considered positive and anti-clockwise as negative. The zero-degree reference was assumed to be the center position of the steering wheel with wheel position straight.
- For lateral acceleration, clockwise was considered positive and anti-clockwise as negative.

5.1.2 DVI Communication Interface

The application output messages from the SAP unit were displayed as notifications using a communication interface implemented using both CAN frames and UDP packets (over Ethernet). The CAN identifier 0x708 was used and the message was transmitted with a frequency of 10 Hz. If no application requested DVI presentation, the application multiplex was set to '0,' otherwise, it was set to the specific application and all the additional application data elements were provided accordingly. The following list shows CAN data output for the implemented applications.

Common for All Applications:

- Flag indicating application
- Distance to the event

RLVW Application:

- Level of urgency (Inform / Warning 1 / Warning 2)
- Lane identified through MAP matching

- Signal phase and time remaining

CSW Application:

- Level of urgency (Inform / Warning 1 / Warning 2)
- Recommended speed (calculated by the algorithm)

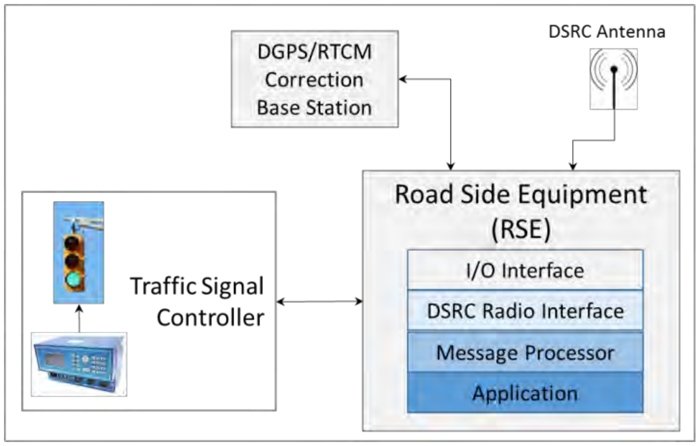
RSZW/LC Application:

- Level of urgency for Reduced Speed and Lane Closure (Inform / Warning 1 / Warning 2)
- Lane identified through MAP matching
- Number of lanes and lane closures in the work zone
- Workers/children present flag in work/school zone
- Set speed limit in the work/school zone

5.2 Infrastructure Architecture

The infrastructure system architecture is shown in Figure 29. The key blocks are described below:

- RSE: An embedded system that included a DSRC radio, computing platform, and necessary Input / Output (I/O) interfaces. Commercially available equipment was used as the RSE for this project.
- Differential GPS (DGPS)/RTCM Correction Base Station: A base station is responsible for providing DGPS/RTCM information to the RSE for packaging and broadcasting a DSRC-based correction message. A commercially available GPS receiver was used for the base station. RTCM version 3.0 message types 1001 GPS L1 observations and 1005 Antenna Reference Point (ARP) station coordinates were used.
- Traffic Signal Controller: A signal controller device responsible for applying a pre-programmable logic to the traffic signal(s). The infrastructure system was connected to an existing traffic signal controller and signal lights owned by CAMP and compliant with the National Transportation Communications for ITS Protocol (NTCIP) 1202 Standard [14].
- Long-term, location-independent security certificates were used for the project. The purpose of using the security certificates was to validate encoding and decoding of the message with security certificates and to validate message authenticity of the sender. The Message Processor shown in Figure 29 encoded the message with a security certificate before broadcasting.



Source: CAMP - V2I Consortium

Figure 29: Block-Diagram of the Infrastructure System Architecture

5.2.1 Infrastructure Requirements

The following requirements are identified for the RSE:

- RSE to transmit local DGPS corrections when available, using the RTCM corrections message format defined in SAE J2735
- RSE to use channel 172 to broadcast Infrastructure-to-Vehicle (I2V) DSRC messages
- For this project, RSE to be programmed to host and execute all implemented applications to enable testing of event relevance algorithm described later in the report
- RSE to synchronize time clock using GPS time
- RSE must be able to sign and validate DSRC messages using the IEEE 1609.2 security standard and store the security certificates
- RSE to implement the DSRC messages that conform to the SAE J2735:2015 version of the standard

5.3 Wireless Message

The existing SAE J2735 standard enables various types of advisory and road sign messages using the Traveler Information Message (TIM) structure. However, it was found that the current structure of the TIM has limitations for supporting the CSW and RSZW/LC applications as intended. This motivated the design of the BIM to support these applications.

5.3.1 Traveler Information Message

As described in SAE J2735, the TIM serves the following purpose:

> *"**Use:** The Traveler Information message is used to send various types of messages (advisory and road sign types) over the WSM [WAVE Short Message] stack to vehicles. It makes heavy use of the ITIS [International Traveler Information System] encoding system to send well known phrases, but allows limited text for local place names. The supported message types specify several sub-dialects of ITIS phrase patterns to further reduce the*

> *number of bytes to be sent. The expressed messages are active at a precise start and duration period, which can be specified to a resolution of a minute. The affected local area can be expressed using either a radius system or a system of short defined regions which is similar to the way roadway geometry is defined in the map fragment messages." [15]*

The TIM structure specifies the mechanisms and data elements for transmitting road sign information and advisories generated by the infrastructure using predetermined International Traveler Information System (IT IS) codes. However, this approach does not consider vehicle-specific information when generating the advisory message. Consider the warning message issued for the CSW application. The TIM may contain the following data elements:

- Type of advisory (dangerous curve)
- Advisory speed
- Location information

This will enable the in-vehicle application to determine whether a warning message should be displayed on the DVI. However, the aforementioned data elements are not an exhaustive list. For example, while superelevation of the curve may prove useful in calculating the timing for a warning; it is not included in the TIM structure.

Additionally, the safety application might be able to make a more informed decision if it can consider both infrastructure and vehicle status information to generate the advisory/warning messages. The application may consider the host vehicle parameters (e.g., weight, height, center of gravity) in conjunction with infrastructure-based parameters such as the curvature of the road to calculate a more relevant advisory speed.

Furthermore, the TIM is limited in describing an event location. The current structure of the TIM supports up to 16 "valid regions" that can be used to create event regions such as the curve of an off-ramp. However, this bound on the number of elements could be problematic for describing complex curves or road work zones that are several kilometers long.

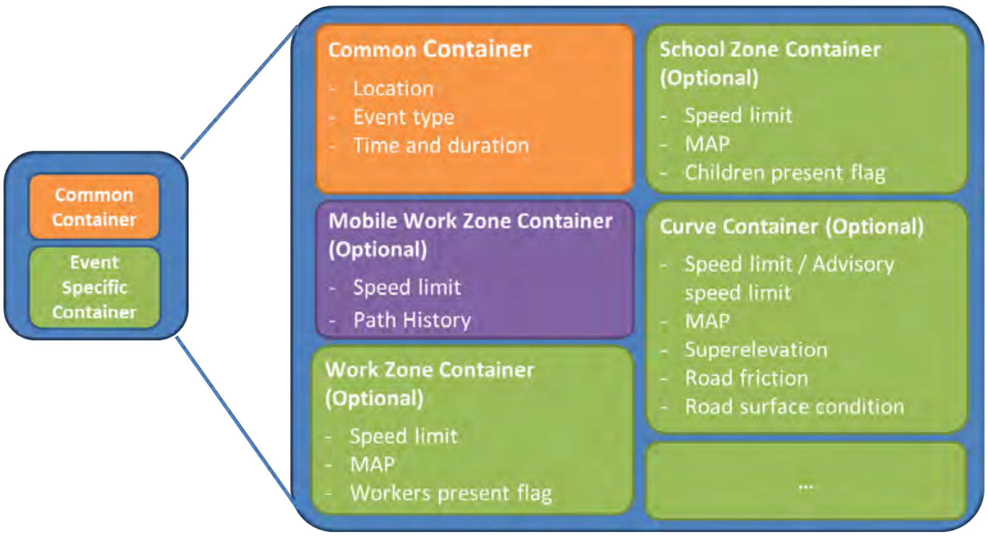
The following list is a summary of the limitations of the current TIM structure for V2I safety applications:

- Road geometries can only be represented by 16 valid regions
- No additional details for particular lanes can be specified other than geometry
- Cannot specify restrictions on the road including types of vehicles restricted for roadway access
- Additional road curvature parameters useful to the CSW application cannot be transmitted to the vehicle (e.g., road friction, superelevation)
- Limited extensibility for V2I use cases as per the message design

5.3.2 Basic Information Message Structure

In this project a new message format that enables the transmission of all required data elements for the current V2I safety applications in a single message was developed and implemented to support testing of the applications. More importantly, this message format should be extensible to support other future event based applications for both V2I and potentially for Vehicle-to-Vehicle (V2V) in the future.

The BIM structure is based on the European Telecommunications Standards Institute (ETSI) standard for the Decentralized Environmental Notification Message (DENM) which has reached a significant maturity and is expected to be adopted for V2I use cases. This concept of message structure uses existing SAE J2735 data elements. As shown in Figure 30, the BIM structure is made of a container concept consisting of a common container that provides basic information elements about an event such as event location, type, time and duration. The event-specific container provides data elements relevant to the event (e.g., speed limits, event MAP, associated flags) for use by on-board applications. Such a concept provides flexibility to extend the message structure by adding containers for future event types (use cases) yet maintaining backward compatibility.



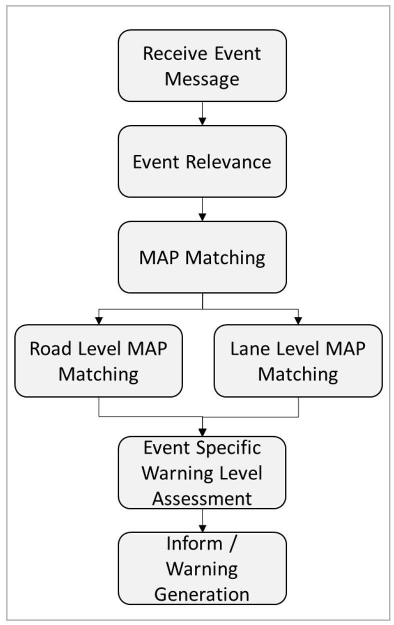
Source: CAMP – V2I Consortium

Figure 30: Basic Information Message Structure

A detailed description of the BIM framework and message elements is provided in Chapter 7.

6 Safety Application Algorithms

In this project, algorithms for each safety application were developed for implementing in prototype OEM vehicles for performance testing and evaluation. Algorithms for all three applications consisted of four main components. A flow diagram depicting the primary components of the safety application algorithm is shown in Figure 31. The components are described in the material below.



Source: CAMP – V2I Consortium

Figure 31: Safety Application Algorithm Components

Event Relevance: This component evaluates the relevance of surrounding zones based on the host vehicle (HV) approach for determining the relevant event for the HV, since potentially the HV may be receiving multiple messages from multiple events.

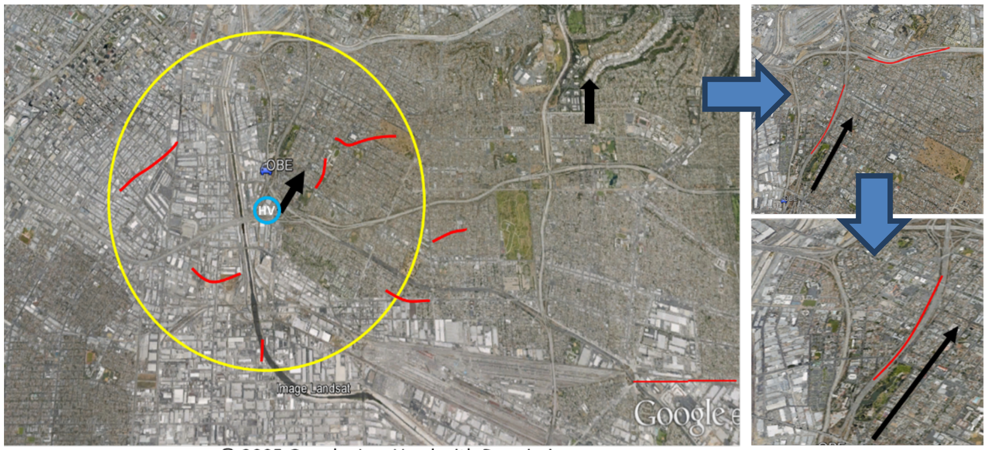
MAP Matching: This component utilizes MAP data received from the RSE for map matching using zone geometry, current vehicle position and vehicle path history. The matching is done either at road-level or lane-level as required for the application. The algorithm also uses DGPS/RTCM correction data in addition to the MAP data for lane-level matching.

Warning Level Assessment: This component runs an application-specific threat assessment algorithm to determine the appropriate warning level. It is based on vehicle speed and position from the event, posted speed limit of the road the vehicle is traveling, several vehicle dynamics parameters and status indicators such as a turn signal and event-specific requirements.

Inform/Warning Generation: This component generates event specific Inform / Warning 1 / Warning 2 messages for outputting to the vehicle DVI.

6.1 Event Relevance Assessment Algorithm

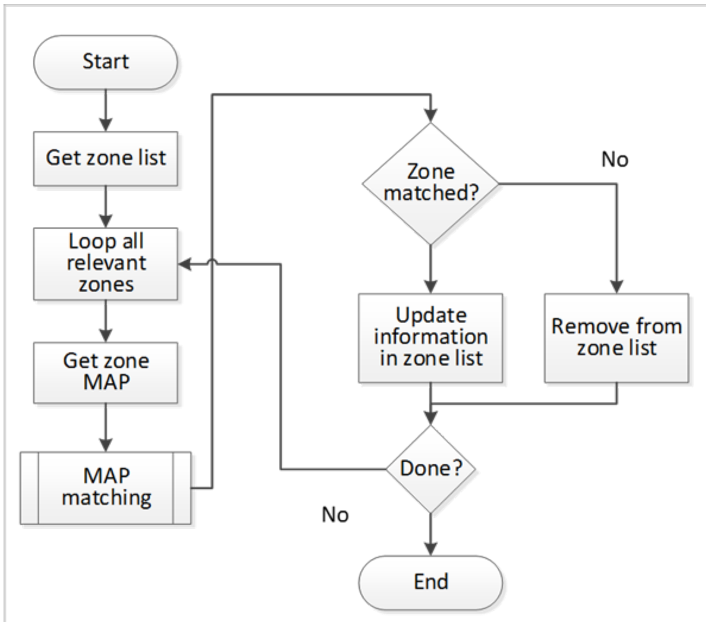
The first step is to assess the zone relevance based on the received event message. Figure 32 presents a graphical representation of event-relevant zone assessment. Figure 33 shows the steps taken in the algorithm for determining the zone relevance.



Source: © 2015 Google, Inc. Used with Permission

Figure 32: Graphical Representation of Event Zones

1. Based on event messages received from RSEs (there could be multiple work zones within communication range of the HV), the algorithm establishes a circular boundary of configurable radius of 300 m (typical DSRC communication range) centered on the HV that may include multiple event zones
2. A list of zones within the circular boundary (HV centered) is constructed and maintained based on the HV approach
3. The algorithm loops through the zone list and drops irrelevant zones from the list based on
   a. Zone that exceeds event validity duration (has passed the time threshold) or outside zone which is outside of the relevance circle around the HV
   b. Rate of distance change between the HV and the reference point of a zone
   c. Zone with positive rate of change
   d. Zone MAP matching is failed
4. For a matched zone, a relevance flag is set and zone list is updated and considered by the specific application algorithm for next step
5. The zone list contains the following data elements
   a. Zone reference point
   b. Distance to the start of the zone
   c. Lane matching status (which of the approach lanes was matched)
   d. Application specific information (e.g., lanes closed, speed limit)



Source: CAMP – V2I Consortium

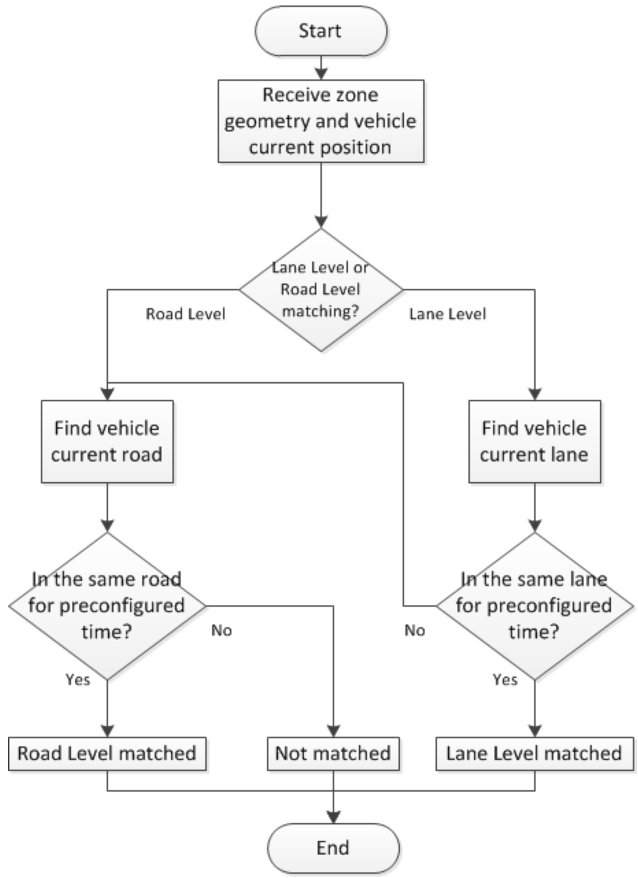
Figure 33: Flowchart for Determining Zone Relevance

6.2 MAP Matching

This sub-algorithm considers zone geometry, the host vehicle's current position and path history to identify if the vehicle's path is matching an approach to the zone. MAP matching is common to all three applications. The designation MAP implies that the map processed by the algorithms is in SAE J2735 format. Figure 34 shows the MAP matching algorithm implemented in this project. The algorithm receives zone geometry information via BIM message and obtains the vehicle’s current and previous positions from the vehicle GPS receiver.

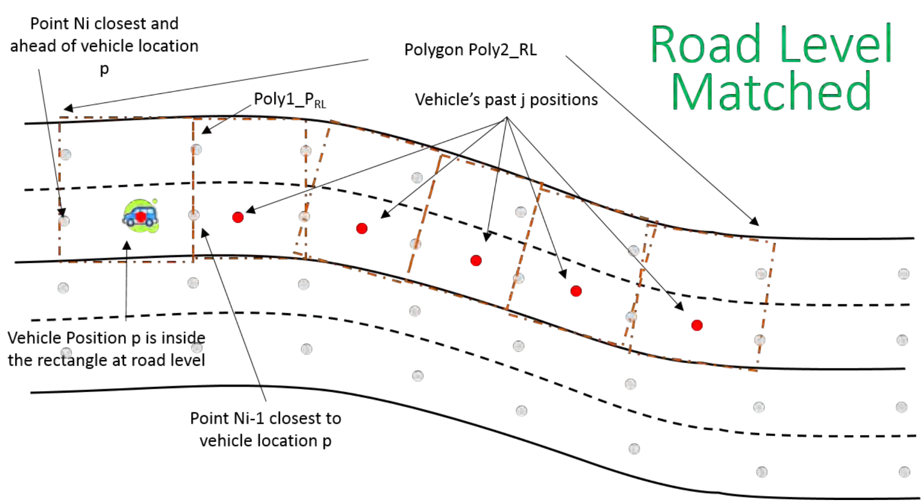
Based on the vehicle current position and received geometry, the algorithm decides whether lane-level matching or road-level matching will be attempted first. Given that lane-level matching was decided, the algorithm verifies whether the vehicle has been travelling in the same lane for a certain configured time with two possible outcomes: 1) The vehicle has been traveling in the same lane, lane-level matching is considered beneficial; 2) The vehicle has not been traveling in the same lane, the algorithm attempts to MAP match the vehicle at a road level. In the case of road-level MAP matching, the algorithm identifies whether the vehicle has been traveling on the same road towards the intersection for a certain pre-configured time with two possible outcomes: 1) If the vehicle has been traveling on the same road, road-level matching is considered successful; 2) if the vehicle has not been traveling on the same road, the algorithm declares a failed MAP matching.

Figure 35 serves as an example of road-level MAP matching. The algorithm identifies the closest point Ni ahead of the vehicle’s current location and point Ni-1 point closest to and behind the vehicle’s position. The algorithm next determines if the vehicle is travelling on the same road, and depending on the vehicle trajectory and GPS accuracy, in the same lane. The algorithm constructs a rectangle from Ni to Ni-1 with: 1) road width in the case of road-level MAP matching; 2) lane width in the case of lane level MAP matching. This process is iterated for consecutive vehicle positions. The algorithm then determines if the vehicle positions remain in the same road/lane for a predefined time threshold.



Source: CAMP – V2I Consortium

Figure 34: MAP Matching Algorithm Flowchart



Source: CAMP – V2I Consortium

Figure 35: Illustration of MAP Matching Process

6.3 Warning Assessment Algorithm

In the following subsection, a warning assessment for each application is described.

6.3.1 Red Light Violation Warning

As mentioned in Chapter 3, the system receives SPaT and intersection geometry information from the infrastructure RSE. The RLVW application combines this information with vehicle kinematic data to determine potential red light violation and generates a Warning message accordingly. The RLVW application is based on the algorithm developed during the previous CAMP Cooperative Intersection Collision Avoidance System – Violations (CICAS-V) Project [16]. In this project, the MAP matching algorithm was extended from the CICAS-V Project to enhance it in the absence of lane-level vehicle positional accuracy which could be caused due to GPS receiver inaccuracy under certain conditions. As depicted in Figure 31, and similarly to the other applications, the RLVW algorithm performs the four steps described below.

6.3.1.1 Event Relevance

The application first decides if the received MAP and SPaT messages are relevant to its direction of travel. This step is based on the CICAS-V [16] algorithm.

6.3.1.2 MAP Matching

Having identified the relevant MAP and SPaT messages, the algorithm next identifies the vehicle’s lane of travel and associated signal phase and time. GPS positioning error may introduce ambiguity in associating the HV to a lane. Hence the following algorithm was developed to predict vehicle position using heuristics (e.g., turn signal, deceleration). This algorithm provides an estimated approach lane for the RLVW application even in the case of non-lane-level localization accuracy.

The algorithm considers the localization accuracy ellipse based on the GPS receiver's Dilution of Precision (DOP) values. If this ellipse (determined by a 1σ probability) covers multiple lanes, these are identified and then filtered based on the following criteria:

- If the same signal phase is assigned to all the associated lanes, selection of a specific lane is not necessary and any one of the lanes can be selected for the warning level calculation
- If on the other hand, lanes associated with multiple phases were selected, then selection of a specific lane is required. Lane selection in the algorithm uses the vehicle turn signal status to determine the turning lane to support this assessment.

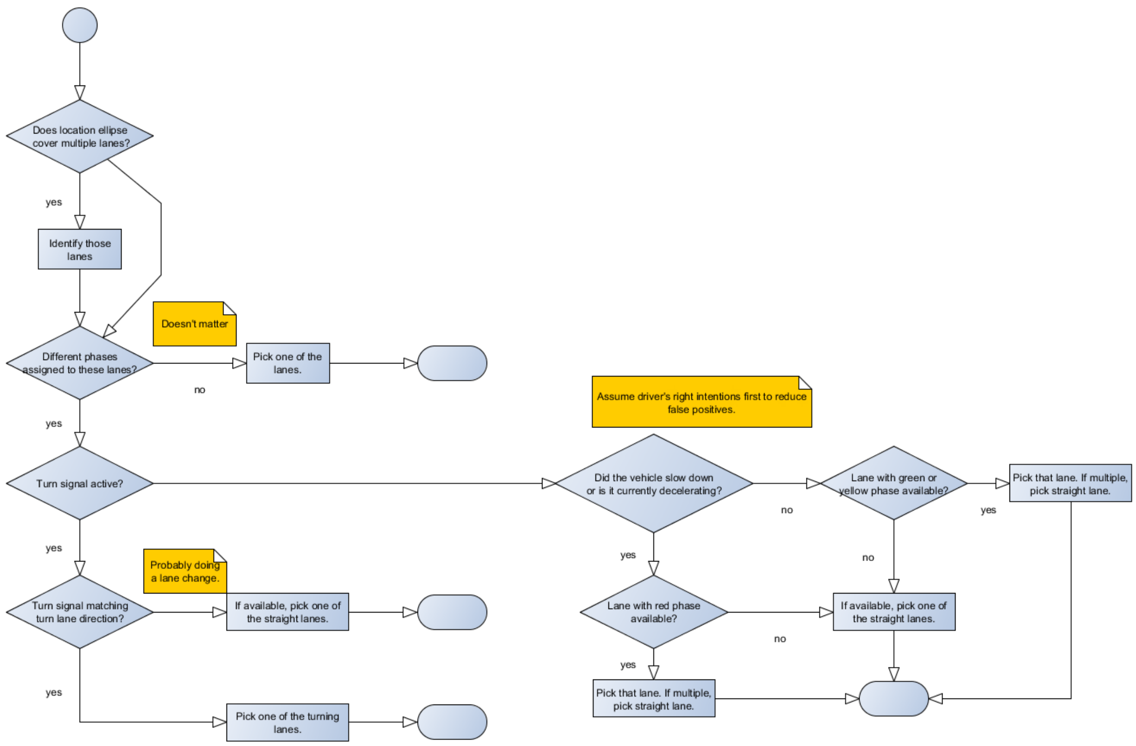
6.3.1.2.1 Turn Signals Active

If the turn signal is active, it is checked if a potential lane candidate matches that traffic direction (e.g., a lane that allows straight and left turn directions would match a left turn signal). If the turn signal does not match one of the lane candidates (e.g., left turn signal active and straight and right turn lane in the list of lanes), it is assumed that the driver is performing a lane change. Therefore, the lane that allows straight through movement is selected.

6.3.1.2.2 Turn Signals Inactive

If the turn signals of the HV are inactive, they cannot be considered and therefore the vehicle's potential deceleration and the current signal phase statuses are evaluated. It is determined if the vehicle slowed down below the speed threshold v_t or if the vehicle is currently decelerating with a rate higher than acceleration threshold a_t. In such cases, the algorithm seeks a lane that currently has the red phase assigned. If a lane with currently assigned red phase is found, it is assumed that the driver is aware of the situation and decelerating to stop at the red light. If no such lane is found, it is assumed that the vehicle is going straight.

If the vehicle was not decelerating, the algorithm checks if a lane with a green or yellow phase is available. In such a case, this lane is selected. Otherwise, a lane going straight is selected. The algorithm flowchart is shown in Figure 36.



Source: CAMP – V2I Consortium

Figure 36: Turn/Lane Prediction Algorithm Flowchart for RLVW

6.3.1.3 Warning Level Assessment

After the system performs map matching and associates itself onto a lane, it performs the following steps to determine if a warning needs to be generated:

1. Determine whether driver is slowing down
    a. If driver is slowing down no warning is generated, go to Step 7
    b. Else go to Step 2
2. Estimate time to stop bar
    a. Calculate distance to stop bar
        i. This is the output of the MAP Matching Algorithm
        ii. It is the 2D distance between HV current position and the stop bar position

   b. Estimate time required by the HV to clear the stop bar using current vehicle speed
3. Using the latest information from SPaT message, calculate the time to red phase
4. Determine if the HV can clear the stop bar
   a. If time to red phase is greater than or equal to the time to stop bar, no warning is generated; go to Step 7
   b. Else Go to step 5
5. Calculate the warning distance
   a. Warning distance is a function which takes into consideration
      i. Speed of the vehicle
      ii. Distance to stop bar
      iii. Driver reaction time
      iv. Vehicle stopping distance
      v. Other system delays
   b. The warning distance equation/mapping will be calibrated during testing
6. Generate Warning
   a. If distance to stop bar is less than warning distance, generate warning; go to Step 7
7. End

6.3.1.4 Hysteresis

As some of these parameters can vary over time, a hysteresis is introduced. For the initial matching, the vehicle's behavior is monitored for a floating time window of t_{h1}. If during that whole window, the calculated lane was constant, this lane is selected.

If a lane was already selected and the selection changed over time, this new selected lane has to be the constant result of the algorithm for t_{h2} in order to become the new selected lane. Table 9 shows the configuration parameters used for the algorithm.

Table 9: List of Configuration Parameters for Turn Prediction Algorithm

Parameter	Default Value	Description
V_t	20 mph	Speed threshold
a_t	2 m/s^2	Deceleration threshold
t_{h1}	1 s	Initial hysteresis time
t_{h2}	1 s	Hysteresis time

Source: CAMP – V2I Consortium

6.3.2 Curve Speed Warning

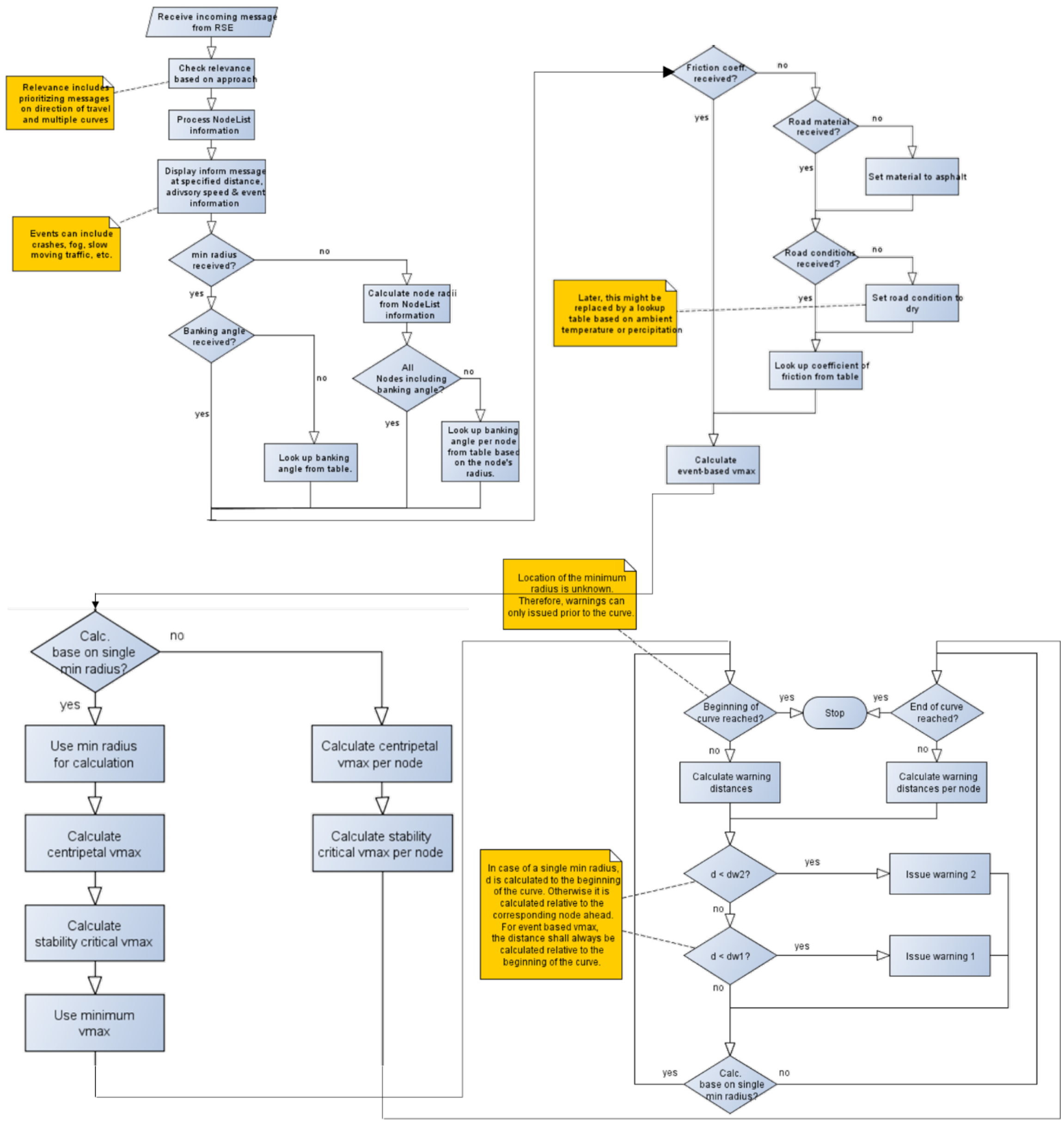
The Curve Speed Warning (CSW) algorithm in the HV processes the BIM specific to an approaching curve and determines an appropriate speed for the HV for travel through the curve. The algorithm will generate necessary Inform, Warning 1, and Warning 2 messages based on the host vehicle's approach speed for the curve.

The CSW infrastructure may transmit RTCM corrections along with the BIM. The BIM for the CSW application may contain one or more of the following data elements:

- Posted speed limit and posted advisory speed limit
- Coefficient of road friction of the curve
- Roadway construction material
- Roadway surface condition (e.g., icy, wet, dry)
- Curve geometry (e.g., minimum radius, superelevation)
- Event on the curve (e.g., stopped traffic on curve, low visibility on curve)

While the basic logic and sequence of steps in the implemented CSW algorithm are common to passenger and commercial vehicles, they differ in the computation of the maximum speed through the curve.

The key computational blocks of the CSW algorithm are for relevance assessment, inform and warning distances, and maximum speed on the curve. A high-level flowchart is shown in Figure 37.



Source: CAMP – V2I Consortium

Figure 37: Curve Speed Warning Algorithm Flowchart

6.3.2.1 Relevance Assessment Calculation

The algorithm will assess the relevance of the received BIM using the MAP matching algorithm described in Section 6.2. The vehicle position relative to the start of the curve is used to compute the appropriate distances for an early notification (Inform), followed by early (Warning 1) and imminent (Warning 2) speed reduction notifications as appropriate. When approaching multiple curved roads, in the current implementation, notifications corresponding to the curved roads on which the HV is traveling are provided.

6.3.2.2 Inform Distance Calculation

The Inform message is an early notification to the vehicle operator about the upcoming event along with any advisory speed information. The inform distance denoted by $d_{\inf}$ is computed using $d_{\inf} = t_{\inf} * v$, where $t_{\inf}$ is the inform time threshold and v is the approach speed of the HV. As an example, assuming a default value of $t_{\inf}$ as 8 seconds, $d_{\inf}$ for $v = 70$ mph and 40 mph was calculated to be 250 m and 140 m, respectively. There is also a provision to override the choice of the parameter $d_{\inf}$ by using OEM-specific HMI implementations. This computation is different than in the case of Warning 1 and Warning 2 messages, both of which are triggered based on the vehicle dynamics and the curve geometry.

6.3.2.3 Maximum Speed on the Curve Calculation

The maximum speed on the curve, denoted as $v_{\max}$, is a function of the vehicle dynamics and some infrastructure-based data such as the minimum radius, coefficient of friction, and the superelevation or bank angle of the curved road. The closed-form expressions for computing the maximum vehicle speed for the curved road are different for passenger and commercial vehicles.

The procedures first obtain the different infrastructure-based data elements are described. When the values of the minimum radius and superelevation of the curved road parameters were present in the BIM, they were used in the computation of $v_{\max}$. If the minimum radius of the curved road is not present in the BIM, then one can compute minimum radius using the road segment information using Sagitta (also known as the versine) [17], a line segment drawn perpendicular to a chord, between the midpoint of that chord and the arc of the circle. The CSW algorithm uses a sequence of three-points along the road segment to iteratively compute the radius of the curved road. In the current implementation, only the innermost lane will be considered for a multi-lane curved road. When the superelevation is not present in the BIM, then these values are obtained from Table 10. The values in Table 10 were derived from surveys published by the Michigan Department of Transportation [18], the excerpts of which can be found in APPENDIX B.

Table 10: Rate of Superelevation as a Function of Radius of the Curved Road

Radius of Curved Road (m)	Rate of Superelevation
r ≤ 68	7%
68 < r ≤ 182	5%
182 < r ≤ 426	3%
426 < r ≤ 915	2%
915 > r	0%

Source: CAMP – V2I Consortium

The coefficient of friction for various road surfaces and road conditions shown in Table 11 was obtained from the book titled Engineering Analysis of Vehicular Accidents [19].

Table 11: Roadway Surface Friction Coefficient

Road Material	Dry	Wet	Snow	Icy
Concrete	0.75	0.6	0.25	0.15
Asphalt	0.65	0.50	0.25	0.15
Dirt or gravel road	0.35	0.35	0.25	0.15

Source: CAMP – V2I Consortium

Three different computations of the maximum vehicle speed on curved roads were considered. The 'Centripetal' $V_{\max}$ was more appropriate for the light-weight vehicles, while the 'Stability Critical' $V_{\max}$ was aimed at capturing the dynamics associated with heavy-duty vehicles. The 'Event Triggered' $V_{\max}$ will come into effect when there are unexpected events such as obstacles on the curved road.

For passenger vehicles, traversing the curved road at Centripetal $V_{\max}$ typically results in tire "breakaway" from the driving surface. However, for heavy trucks with a much higher Center of Gravity (COG), usually, $V_{\max}$ is the limit for vehicle rollover. The closed-form expressions vary depending on the vehicle configuration (e.g., tractor-trailer combinations), but the most important piece of information is that the COG of a loaded tractor-trailer configuration will continually change and estimating this accurately and representing it as a closed-form solution is quite challenging. This can be achieved via vehicle sensing or an empirical look-up table. So, the Stability Critical $V_{\max}$ depends on the height of the COG and is the key distinguishing feature. Table 12 summarizes the procedure to compute $V_{\max}$.

Table 12: Computation of $V_{\max}$

Speed	Description
Centripetal $V_{\max}$ [20]	$Vmax = \sqrt{\frac{r * g * (\tan(\emptyset) + \mu)}{1 - \mu * \tan(\theta)}}$ where: r is the minimum radius of the curved road, $g = 9.8$ m/s^2, θ is the superelevation, and μ is the coefficient of friction for the curved road surface; a reconfigurable factor of safety of 65% is applied to μ for computing

Speed	Description
Stability Critical $V_{\max}$	$Vmax = \sqrt{r * g * \left(\left(\left(\frac{T}{2h}\right) * \propto\right) + \tan \emptyset\right)}$ where: α is the 'reduction factor' due to compliance and backlash effects in tires, suspension, and frame, and lies between 0.6 and 0.8; T is the track width and ranges from 1.8 to 2.5 m; h is the height of the center of gravity, also in meters; and the rest of the parameters are as previously defined in the formula above.
Event Triggered $V_{\max}$	In the event, such as an obstacle on the curved road or poor visibility is indicated in the BIM, a set $V_{\max}$ is used: 1. If 'obstacle' flag in the BIM is present, $V_{\max}$ is set to a configurable speed of 15 mph 2. If 'reducedVis' flag in the BIM is present, $V_{\max}$ is set to a configurable speed of 35 mph 3. If neither is present in the BIM, no $V_{\max}$ is calculated and set to 0. In the current implementation, only two scenarios, namely stopped vehicle or low visibility notification have been considered for alternate maximum speeds.

Source: CAMP – V2I Consortium

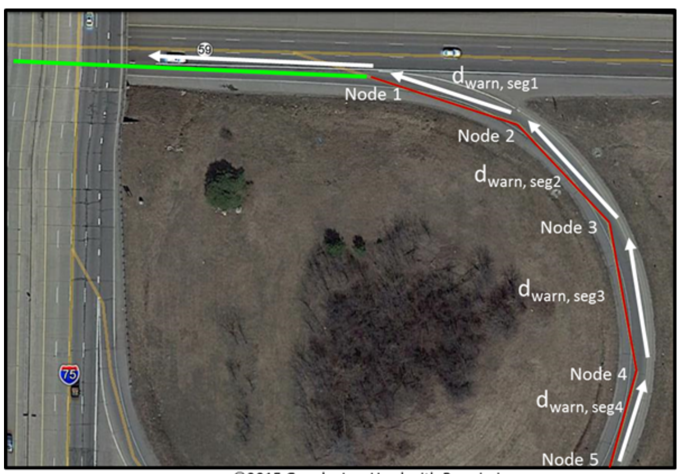
For future implementations and potential deployment, it would be beneficial for the infrastructure to have a data field to dynamically indicate an appropriate reduced speed based on event on the curve conditions. Lastly, if the radius of the curved road was calculated segment by segment (i.e., if the parameter is not present in the BIM), $V_{\max}$ will be iteratively computed for each segment.

6.3.2.4 Warning Distance Calculation

Warning distance computations are based on $V_{\max}$. In case of multiple $V_{\max}$ values, warning distances are iteratively computed for each $V_{\max}$. Two speed reduction notifications are generated by the in-vehicle application, namely Warning 1 and Warning 2 messages. The distance at which Warning 1 will be issued corresponds to the distance needed for the driver to decelerate the vehicle from its current speed (also referred to as the curve approach speed) to the computed $V_{\max}$ at a configurable deceleration rate of 2.4 m/s^2.

Warning 2 will be issued at a distance that will enable the driver to decelerate the vehicle from its current speed to $V_{\max}$ at a configurable deceleration rate of 4.6 m/s^2. The closed-form expression for calculating the warning distances is given by $d = \frac{v_{max}^2 - v^2}{2a}$, where d is the warning distance, V is the curve approach speed, and a is the deceleration rate. It is remarked that the deceleration rates would be modified as needed during subsequent application testing. These computed warning distances were always compared with the distance of the HV from the curve.

Figure 38 provides an example of how warning distances will be laid out on a curve. As shown, a curve can be represented by nodes and the warning distance is calculated for each node segment. For an event, such as approaching the curve, the warning distance is computed from the beginning of the curve shown as Node 1. For each node segment shown in red, the radius of curvature for the node segment and associated $V_{\max}$ is computed. As the vehicle approaches the subsequent node segment, the associated warning distance is computed as $d_{arn, seg1}$, $d_{warn, seg2}$, $d_{warn, seg3}$ and so on as shown in the figure. In this example, assume that the computed radius of segment 3 is lower than the previous segment 2. In such a case, the d_{warn} generated for segment 3 would supersede the d_{warn} generated for segment 2 when the vehicle speed is above the $V_{\max}$ for segment 3.



Source: ©2015 Google, Inc. Used with Permission

Figure 38: Example of Warning Distances Determination for CSW

6.3.3 Reduced Speed Zone Warning / Lane Closure

The RSZW/LC in-vehicle algorithm receives a work zone / school zone message from the relevance assessment algorithm and calculates the Inform and Warning levels for the reduced speed and lane closure use cases.

As described earlier the HV receives BIM messages from the infrastructure. The relevance and MAP matching algorithms determine the reduced speed zone/work zone event for the HV followed by the warning level assessment and issuance of proper Inform/Warning.

Figure 39 depicts the flowchart for the warning level assessment algorithm. The initial step of the algorithm is to calculate the appropriate warning distance and inform distance based on the vehicle's current speed. This is done using the following formulas:

$$d_{inf} = v * t_{inf}$$
$$d_{warn} = v * t_{warn}$$

where:

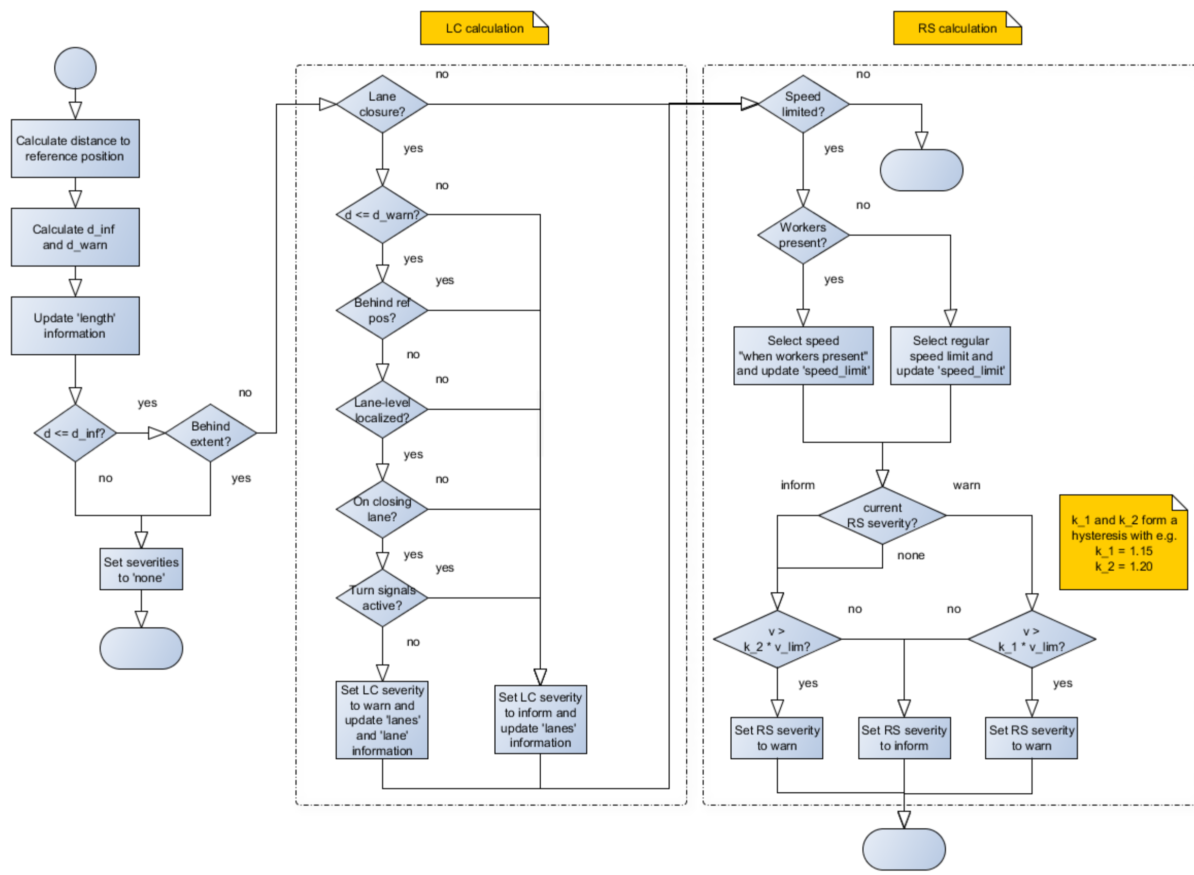
d_{inf} = *inform distance (m)*

d_{warn} = *warning distance (m)*

t_{inf} = *inform time threshold (s)*

t_{warn} = *warning time threshold (s)*

V = vehicle velocity (m/s)



Source: CAMP – V2I Consortium

Figure 39: Warning Level Assessment Algorithm Flowchart for RSZW/LC

The RSZW/LC application algorithm will warn when the configurable vehicle speed is 7 mph above the posted speed limit to avoid fluctuation in warning and annoyance to the driver when the driver closely maintains the vehicle speed to the posted speed limit.

6.3.3.1 Algorithm Inputs:

Table 13 lists the data element input for use by the RSZW/LC algorithm.

Table 13: Data Elements for RSZW/LC Algorithm

Input	Type/Values
Zone type	0x00 - Nothing; 0x01 - Work zone; 0x02 - School zone
Work zone geometry	As ‘DF_RoadSegmentList’ in J2735
School zone area	As ‘DF_NodeList’ in J2735
Speed limit	As ‘DF_SpeedLimitList’ in J2735
Worker present status	0x1: workers present flag; 0x0: information not available
Vehicle position	As ‘DF_Position3D’ in J2735 including Latitude, Longitude, Elevation
Vehicle path history	As ‘DF_PathHistory’ in J2735
Vehicle speed	As ‘DE_Speed’ in J2735
Vehicle acceleration	As ‘DF_AccelerationSet4Way’ in J2735
Vehicle turn signal status	As ‘DE_ExteriorLights’ in J2735

Source: CAMP – V2I Consortium

6.3.3.2 Algorithm Outputs:

The algorithm produces outputs listed in Table 14.

Table 14: RSZW/LC Algorithm Output

Output	Type/Value
Zone type	0x00 - nothing; 0x01 - Work Zone; 0x02 - School zone
Reduced speed severity	0x00 - nothing; 0x01 - inform; 0x02 - Warning 1; 0x03 - Warning 2
Lane closure severity	0x00 - nothing; 0x01 - inform; 0x02 - Warning 1; 0x03 - Warning 2
Enforced speed	x m/s
Length (remaining) of the work zone	x*10 meters
Number of lanes	1..8; 0 – unknown; 9-15 - unused
Lane closed	0000 0000 - None/Unidentified; 0000 0001 - rightmost lane closed; 0000 1100 - In a four-lane scenario: Two leftmost lanes closed; 0100 0000 - In a seven-lane scenario: Leftmost lane closed
Selected lane	1..8; 0 – unknown; 9-15 - unused

Source: CAMP – V2I Consortium

7 Framework for Basic Information Message

As described in Section 5.3.2, the BIM structure is based on a container concept. In this context, a container is defined as a collection of data elements that provide basic information about an event. Such a concept provides flexibility to extend the message structure by adding containers for future events (use cases) yet maintaining backward compatibility. The BIM developed for the project consists of four containers: The Common Container, the Mobile Container, the Work Zone Container, and the Curve Container. The BIM data elements developed for each container are described in this section. The data element name, whether mandatory, optional or conditional for the message, type, and description are listed in tables for each container. BIM uses the same data element type as defined in SAE J2735 where available.

7.1 Common Container

As the name suggests, the Common Container provides common data elements that identify the event and relevant information about the event (e.g., message ID, event ID, time and duration of the event, reference position, speed limits) as listed in Table 15. Several data element types used are the same as defined in SAE J2735.

Table 15: Data Elements for a Common Container

Common Container Contents	Mandatory / Optional / Conditional	Type	Notes
DSRCmsgID	M	As ‘DSRCmsgID’ in J2735	BasicInformationMessage Until an ID is assigned, ‘142’ shall be used.
eventID	M	As ‘DE_TemporaryID’ in J2735	Unsigned 32-bit integer randomly generated at the time of event (same structure DE_TemporaryID)
segmentID	O	As ‘DE_TemporaryID’ in J2735	A more complex (e.g., longer) event can be described by multiple messages transmitted by multiple stations. In that case, these multiple messages can be linked together using the segmentID.
dateTime	M	As ‘DF_DDateTime’ in J2735	Time of detection of the event – same as DF_DDateTime
duration	M	As ‘DF_DDateTime’ in J2735	Time duration from dateTime before which the event is unlikely to change, includes a value indicating infinite.
causeCode	M	An unsigned 8bit integer representing seconds	Identifies type of event (e.g.,hazardousLocation-DangerousCurve , roadworks , etc.).

Common Container Contents	Mandatory / Optional / Conditional	Type	Notes
			Based on codes from the ETSI/ISO DENM standard.
subCauseCode	O	An unsigned 8bit integer representing event types	Provides more detailed information of the event related to the causeCode. The value of subCauseCode uses the ETSI DENM standard approach, which is based on the TPEG TEC specification as defined in TISA TAWG 1071 [i.10].
referencePoint	M	As 'DF_Position3D' in J2735 including Latitude, Longitude, Elevation	Reference position of the beginning of the event – same structure as DF_Position3D. Used as the reference for all subsequent sequences of GenericLane and corresponding nodes.
applicableHeading	M	As 'DE_Heading' in J2735	Identifies applicable direction of travel – DF with unsigned integers for both heading and tolerance (both in increments of 1 degrees)
speedLimit	O	As 'DF_SpeedLimitList' in J2735	Speed limit at the reference position
roadWidth	C (approachLanes)	As 'DE_LaneWidth' in J2735	Road width at the reference position, if multiple lanes, the combined width of all lanes. Must be present it approachLanes does not contain an instance of GenericLane for every lane.
approachLanes	M	As a sequence(1..10) of 'DF_NodeList' in J2735	Sequence of up to 10 lane numbers assigned to the corresponding affected approach lanes (from left-most – lane 1, to right-most lane) – same structure as DE_LaneID, and optionally a corresponding instance of GenericLane.
eventLength	O	Proposed to use ED_Extent if it has more granularity -- OR Use – DE_ZoneLength but do not restrict up10 10,000m. Modify to support full 16bit integer.	Length of the event in meters (in terms of distance of travel – not a straight line between points). Could use DE_Extent if it had more granularity (suggest to change to unsigned integer).

Source: CAMP – V2I Consortium

7.2 Mobile Container

The Mobile Container specifies the data elements related to either temporary or moving work zone areas. For example, this container could be added for a moving road work area such as lane marking patching in progress. The Mobile Container can also be used with other application container such as the Work Zone Container. Data elements for the Mobile Container are shown in Table 16.

Table 16: Data Elements for a Mobile Container

Mobile Container Contents	Mandatory / Optional / Conditional	Type	Notes
Speed	M	As 'DE_Speed' in J2735	Speed of the event movement
Path	O	As 'DF_PathHistory' in J2735	

Source: CAMP – V2I Consortium

7.3 Work Zone Container

The purpose of the Work Zone Container is to communicate the work zone-related parameters for use in the RSZW/LC application. In addition to defining the geometry of the work zone as specified in the SAE J2735 standard, the data elements provide information about the number of lanes and lane specific closure information including presence of workers. It contains the data elements as listed in Table 17.

Table 17: Data Elements for a Work Zone Container

Work Zone Container Contents	Mandatory / Optional / Conditional	Type	Notes
laneStatus	M	An 11bit bit field	A sequence of laneIDs (from approachLanes) and their corresponding status (open or closed). Bit field that describes the number of lanes the road has and which lanes are open and which are closed. The leftmost '1' in the field is a delimiter to specify the number of lanes the road has. '00010000' means that the road has four lanes and all are open. Every '1' right of that first '1' indicates that the corresponding lane is closed.

Work Zone Container Contents	Mandatory / Optional / Conditional	Type	Notes
laneCloseOffset	M	A list of up to 10 as 'DE_ObstacleDistance' in J2735	A list of offset distances from reference point that describe lanes closures, if any, for all work zone lanes represented in the BIM (laneStatus). Same structure as DE_ObstacleDistance – use distance traveled, not a straight line
geometry	C (eventLength)	As 'DF_RoadSegmentList' in J2735.	A sequence of GenericLane. Must be present if eventLength is not present in the common container. LaneIDs are carried over from approachLanes in the common container.
workersPresent	O	Activity	Binary flag indicating whether or not workers are present

Source: CAMP – V2I Consortium

7.4 Curve Container

The Curve Container is used to communicate road curvature related data elements for use in CSW application. It contains the data elements listed in Table 18.

Table 18: Data Elements for the Curve Container

Curve Container Contents	Mandatory / Optional / Conditional	Type	Notes
frictCoeff	O	An unsigned 7bit integer 0..100 with a unit of 0.01, effectively representing values between 0..1	Coefficient of (kinetic) friction for a reference tire sliding over the surface under dry conditions
advisorySpeed	O	As 'DE_Speed' in J2735	Advisory speed that may be displayed if the vehicle cannot calculate the warning speed.
geometry	C (minRadius)	As 'DF_RoadSegmentList' in J2735.	A sequence of GenericLane. LaneIDs are carried over from approachLanes in the common container.
surfaceCondition	O	An enumerated value	Consider ITIS codes (need dry, moist, wet, flowing, ice, snow, frost)

Curve Container Contents	Mandatory / Optional / Conditional	Type	Notes
material	M	An enumerated value	Enumeration containing material type (asphalt, concrete, brushed concrete, …)
minRadius	C (geometry)	Radius	Minimum radius of the curve (in meters)
bankAngle	M	A signed 7 bit integer representing positive and negative degrees (-63..64)	Bank angle of the curve at the minimum radius
obstacle	O	Activity	Binary flag
reducedVisibility	O	Activity	Binary flag

Note: When both lane geometry and minRadius are provided in the BIM, the minRadius will be used to calculate V_{max}.

Source: CAMP – V2I Consortium

7.5 Basic Information Message Encoding

The SAE J2735 standard specifies message encoding for efficient transmission of the DSRC message in Abstract Syntax Notation revision One (ASN.1). This is a standard notation that describes rules and structures for representing, encoding, transmitting, and decoding data in telecommunications and computer networking. The formal rules enable representation of objects that are independent of machine-specific encoding techniques. The ASN.1 structure for all four BIM containers is shown in APPENDIX C

7.6 Minimum Performance Requirements

The BIM format is generic in nature and supports different types of applications as well as different granularities for the same application. Therefore, it is important to establish minimum performance requirements that define:

- Which data elements in the BIM are mandatory, optional or conditional and which are required
- How the data elements shall be filled
- The level of accuracy required for each of the elements

This is necessary to establish a common understanding between the infrastructure and the vehicle side of the application and to ensure that the vehicle side can rely on certain required data elements that are critical to intended safety application behavior.

The following subsections describe a high-level overview of the requirements for the three applications and different implementation complexities.

7.6.1 General Requirements

The following performance requirements are not use case specific but generic in nature to ensure a common generation and interpretation of BIMs.

7.6.1.1 Event detection

- For any of the required message fields cannot be filled, the message shall not be transmitted.

7.6.1.2 Message Transmission

- The message is encoded using the UPER encoding scheme.
- The event detection time shall be set to the time when the criteria for the event were first met.
- The duration the event is valid for shall be transmitted and shall be set to an application specific value. Depending on the data sources for the detection of the event, a longer or a shorter event duration might be appropriate.

7.6.1.3 Message Repetition

- The message shall be repeatedly retransmitted with the application specific retransmission interval as long as the conditions continue to meet that caused the transmission.
- When the transmission criteria are still valid but the validity duration of the message is reached, the transmitting station shall update and transmit the message.
- Whenever an event message is updated (either because parameters have changed or the validity duration of the original message has reached), the detection time shall be changed to the time when the update was conducted.
- In case of an update of an event, the event identifier shall be kept the same for identification purposes on the receiver side.

7.6.2 Approaches

Approaches help a receiving vehicle determine relevance of the described event for their current path of driving. The message format allows the definition of multiple approach lanes per event to be able to model lanes that lead (or don't lead) to the event. Additionally, when connecting approach lanes to the approaching event (such as a work zone or curvature), the lane geometry shall be explicitly defined in cases where such connections exists.

7.6.2.1 ApproachClassification

The optional data element ApproachClassification allows the classification of approach lanes based on the certainty with which they lead to the event. This can be used in locations where criticality of the event differs depending on the driver's route choices. Whenever the message generator has knowledge about this information, it shall be used to specify the classification accordingly.

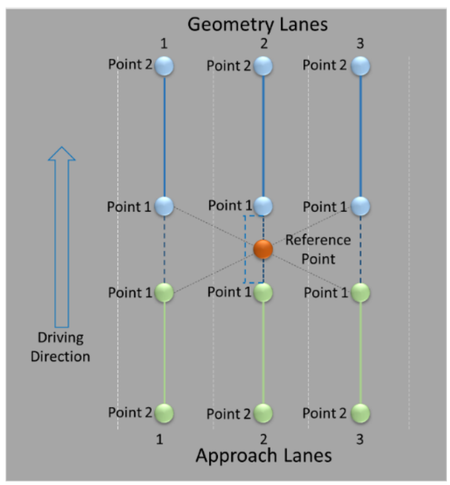
If approach classification for a specific approach lane is not given, a receiver shall assume that this lane will lead to the event.

7.6.2.2 Lane Layout

The message format supports multiple approach lanes and (depending on the use case) multiple geometry lanes. The following general rules apply to the layout of those lanes:

- Lanes are always defined away from the reference point. Therefore, vehicles are traversing an approach lane against the definition and geometry lanes with the definition.
- The potential connection between the reference point and any first lane node point shall not be used for map matching. Those can be seen in the graphic below as dashed lines.
- All approach lanes that logically connect to one or more geometry lanes shall specify this connection through the connectsTo data frame.
- A "connection" is defined as an approach lane physically leading to a geometry lane without requiring to perform a lane change maneuver.

Figure 40 shows a graphical example of an application that supports three lanes (e.g., a work zone message). The event begins at the Reference Point and three approach lanes describe trajectories into the work zone. In the work zone, the three geometry lanes describe paths throughout the work zone. The connection between the first approach and geometry lane nodes that a receiver can make through the connectsTo data element is shown in dashed blue.



Source: CAMP – V2I Consortium

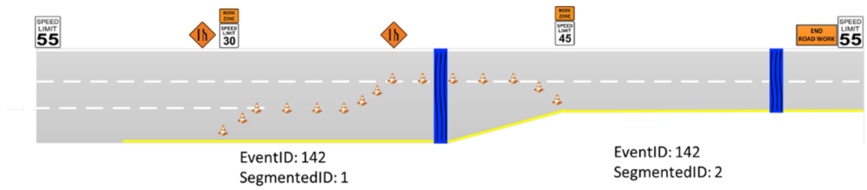
Figure 40: Graphical Example of Layout of Approach and Geometry Lanes

7.6.3 Usage and Example of SegmentedID

- SegmentedID is intended to link messages representing a particular event spanning over large geographical area, or requiring multiple messages representation due to increased complexity.
- The example graph in Figure 41 shows an example of SegmentedID being implemented on a long work zone with multiple lane closures and speed limits.
  - The first segment, having SegmentedID of 1, has two lanes closures and a reduced speed limit of 30 MPH.

- The second segment, having SegmentedID of 2, has a reduced speed limit of 45 MPH.
- Notably, EventID remain the same in both segments messages to indicate that both segments belong to the same event, same work zone in this particular case.

- Certain optional data elements in common container may not need to be sent in the messages representing segments beyond the first segment. For example:
    - Approach: Instead, vehicles can use "connectTo" data frame to continue map matching from geometry lane in a particular segment to the geometry lanes in the subsequent segment.

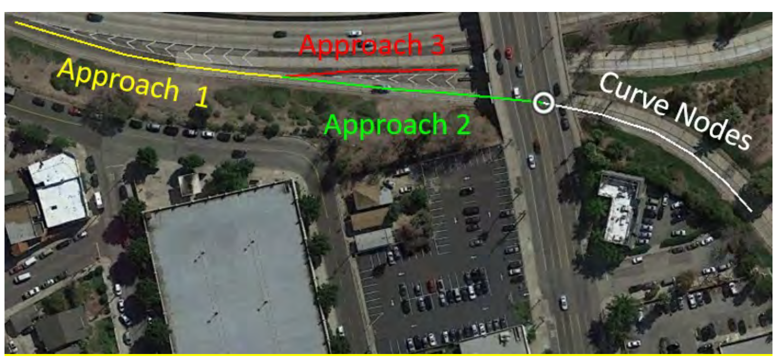


Source: CAMP – V2I Consortium

Figure 41: Graphical Example of Usage of SegmentedID

7.6.4 Curve Speed Warning

An accurate geometric representation of the road is critical to the Curve Speed Warning Application. It is assumed that all lanes leading to the curve that is being described are represented by an approach data element. This is necessary because the application will only issue warnings when the vehicle is successfully MAP-matched to one of the approach lanes. This is used to suppress false warnings in scenarios where, for example, an off-ramp is leading to a curve but other adjacent lanes continue straight as depicted in Figure 42.



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 42: Example Approach to a Curve Event

7.6.4.1 Recommended Guidelines

For the actual curve geometry, the map accuracy becomes even more important as the in-vehicle algorithm derives the curve radii from the geometry and can thus react appropriately to varying radii. This, however, requires the geometry nodes to follow certain criteria.

- The approach geometry (list of nodes) is used to determine if the event is relevant to the approaching host vehicle.
- The length of the mapped geometry of the approach lane shall be sufficiently long so that the in-vehicle application can inform the driver about approaching a curve to take an appropriate action if needed. Recommended length in meters shall be equal to five times the posted speed limit of the approach lane or longer. Sufficiently long mapped approach may include uncertain portions of the approach which may not lead to the curve.
- The curve geometry (list of nodes) can also be used to calculate radius of the curvature, if radius is not specified in the BIM. The node list points must be placed with a certain accuracy for the in-vehicle application to accurately calculate radii based on node segments for generating appropriate information by the host vehicle prior to entering the curve segment. This method allows non-uniform multi-radii curve or varying radii curvature.

The reference point indicates start of the curve event. All event related information (curve radius, friction coefficient, visibility, obstacle, road surface, etc.) is to be applied after this point. The reference point shall be placed between the first node of the Approach and the first node of the Curve geometry with a close enough distance as shown in Figure 43. The red pin indicates reference point, yellow dots for approach and blue dots for curve geometry.

Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 43: Example - Placement of Reference Point and First Node Point of Approach and Curve Geometry

- The curve geometry can represent information either at a road-level or at a lane-level. In a multiple lane scenario, either:
  - A “lane width” covering the width of all lanes and one “lane” located in the middle of the multiple lanes (This method is not preferred, as there seems to be no way to specify in the map that this is a “road-level” map.)
  - A “lane width” equal to the actual lane width and a description of each lane shall be provided
- If the curve is drivable in both directions, a separate message for each direction with their corresponding approaches shall be issued.
- If the surveying accuracy of the geometry is not sufficient for node by node radius computation, the infrastructure shall provide the 'minRadius'

7.6.4.2 Surveying Requirements

Accuracy requirements for generating maps is described below.

- For approach lane(s) leading to the curve, general accuracy requirements for lane level map matching apply. The lateral accuracy of the placement of nodes and the lane or road width should be within 0.5 m accuracy.
- For the curve geometry, following two cases can be considered:
  - The node points for defining the curve geometry do not have to be placed equidistant from each other. However, the distance between adjacent nodes can be derived based on the radius of the curvature as:

    Distance between adjacent nodes [m] = 0.058 x {(radius of the curve [m]) - 40m} + 12.5 m.

    The distance between adjacent nodes cannot be smaller than 10% of the minimum radius of the curve
- Node points should be placed in the center of the lane (or road) that is being mapped. The relative lateral and longitudinal error of those points should be contained within 0.05 m. It should be noted that this is only a relative accuracy requirement since multiple points together are used to compute radius of a curve segment. Relative placement of a single point among multiple points off by a few centimeters may significantly impact radius calculation. However, the absolute accuracy requirements are less stringent and a lateral and longitudinal accuracy of the overall curve geometry of < 0.5 m is acceptable.
- The relative accuracy of the node points shall be < 0.1 m

If the recommended accuracy cannot be met, minimum radius of the curve shall be provided. In such case, the in-vehicle application will consider single radius and not multiple varying radii.

It is desired that the infrastructure, in addition to geometry related information, also provide road surface condition. Ideally, it would be desirable that the current estimated coefficient of friction is provided through an Environmental Sensor Station (ESS). It is understood that such equipment might not be available at all locations. In that case, it is required that the road material and estimated surface condition (e.g., dry, wet, icy) is provided.

If an advisory speed sign is posted for the curve, the infrastructure shall also provide the value in the message transmission for incorporating into the warning algorithm or for display purposes to the driver.

7.6.5 Reduced Speed Zone Warning

When the RSZW application is applied to work zones, certain guidelines must be followed as well. Two levels of infrastructure implementation are envisioned and depicted in the message format:

- The infrastructure has detailed information about the work zone geometry and can provide a lane-level map including information about the location of potential lane-closures. In this case, the vehicle can perform lane-level map matching and provide warnings to drivers that drive on a closing lane. While this provides better results and more accurate warnings in the vehicle, this also requires more detailed information from the infrastructure that might not always be available.

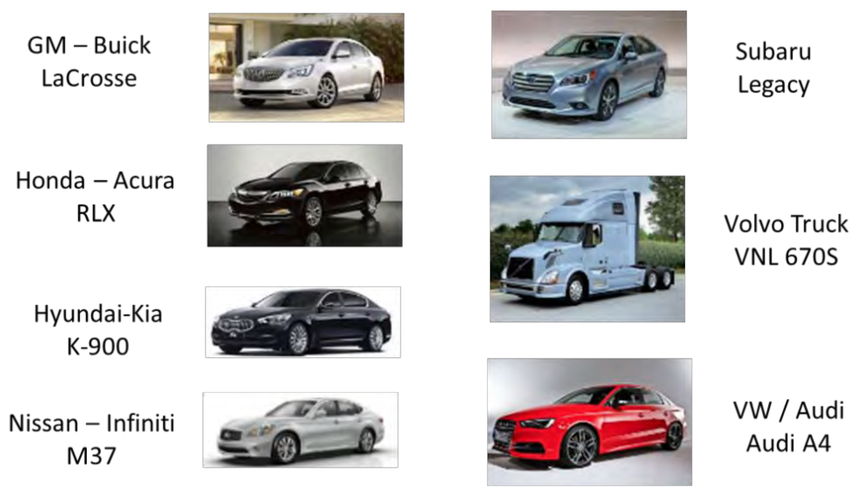
- The infrastructure system is limited in that it has no access to a backend with additional map data. This might be the case for a standalone installation such as on a warning trailer. In that case, it is assumed that a map cannot be provided. It is required, though, to indicate the number of lanes, which of them are closed and the length of the work zone. This is information that would be available on-site and could be entered by a worker.

8 Vehicle Integration

This section provides a description of the test vehicles, an overview of the development of the in-vehicle systems, and the integration (hardware layout and wiring schematics) of the required components into the test vehicles.

8.1 Test Vehicles

The CAMP V2I Consortium integrated the test systems into seven vehicles that included six passenger vehicles (by Honda, Hyundai-Kia, GM, Nissan, Subaru, and VW) and a Class 8 commercial vehicle (by Volvo) as shown in Figure 44.



Source: CAMP – V2I Consortium

Figure 44: Test Vehicles for Safety Applications

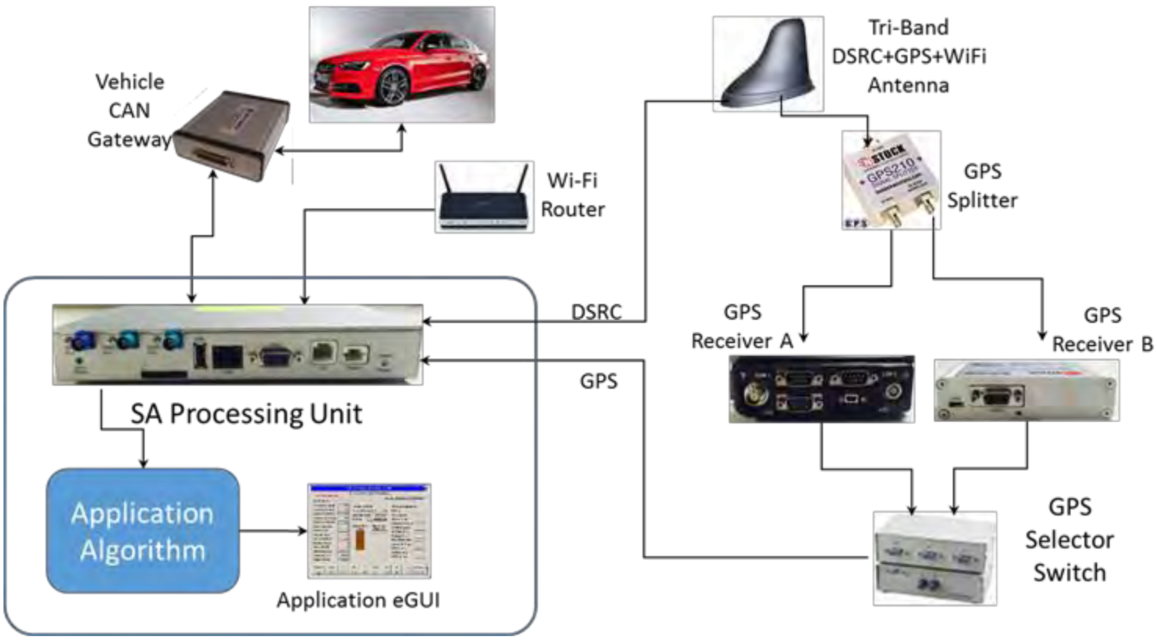
8.2 Test Vehicle Hardware Architecture

The basic hardware setup to support the in-vehicle application development was common to all the participating OEMs. This section describes the test hardware, layout, and the relevant wiring schematics to support vehicle integration.

8.2.1 Vehicle Component and Interface Layout

Figure 45 shows a high-level layout of the key hardware components that were integrated with the test vehicles. The SAP unit within the vehicle-based subsystem received the V2X (i.e., V2V or V2I) DSRC messages, GPS data, and vehicle status data either through the CAN interface or through BSM proxy, and provided an interface to the DVI in the vehicle for driver information.

Many components are common across all the test vehicles, including the SAP unit comprised of a dual radio unit for DSRC communication, an interface to the GPS receiver, CAN interface for vehicle data, an Ethernet interface for communication with external devices, and a USB interface for data logging. The DSRC software stack was implemented in the SAP unit and supported the in-vehicle applications. The Wi-Fi router provided remote access to the SAP unit for performing software updates and downloading logged data. The eGUI enabled a visual display for monitoring and debugging key parameters in addition to the Inform and Warning messages as produced by the application algorithm, but not intended to serve as basis for the end-user information display.



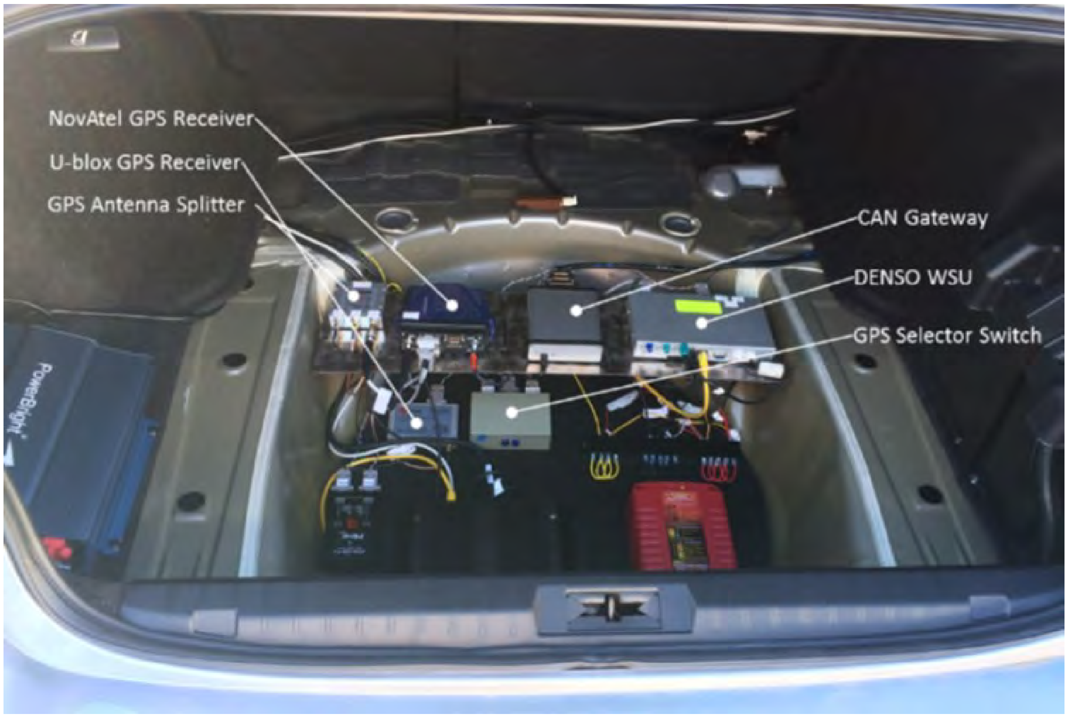
Source: CAMP – V2I Consortium

Figure 45: Hardware Component Layout

The GPS data unit consisted of two GPS receivers: 1) receiver A for supporting RTCM corrections and 2) an automotive grade receiver B. A user selectable switch provided input to the SAP unit for the selected GPS receiver, thereby enabling GPS data input with and without RTCM corrections.

Each OEM integrating the safety applications into their vehicle was responsible for providing vehicle status data to the SAP unit for use by the application algorithm either using the CAMP CAN connection or by providing BSM data over the UDP connection.

The six passenger vehicles used a tri-band (supporting DSRC, GPS, and Wi-Fi signals) shark-fin antenna, while the Volvo truck used a pair of spring-loaded antennas integrated into a side rear view mirror. The key differences were the form-factor and antenna gains, both being larger in the case of the commercial vehicle. The Subaru Legacy, an example of a fully integrated hardware component in an OEM test vehicle, is shown in Figure 46.



Source: CAMP – V2I Consortium

Figure 46: Picture of Integrated Hardware in a Test Vehicle

8.2.2 DVI Interface

Two different approaches were implemented to enable the visualization of the outputs of the in-vehicle application. The first approach was the use of the eGUI that resided on the SAP unit and served to display, monitor, and debug key parameters that were specific to each safety application that was implemented. The eGUI essentially provided a large volume of data in addition to inform and warning messages, and aided testing and parameterization of the safety algorithms to ensure proper functioning. Because the SAP unit does not have a video output, the eGUI can only be accessed over Ethernet using the VNC protocol. This can then be displayed either on a laptop or on a vehicle mounted display connected to the vehicle PC.

The second approach is an interface developed by the V2I-SA project team for this project. The outputs of the in-vehicle application are made available both on the vehicle CAN bus and on Ethernet using UDP for access by the vehicle DVI that can use this information to trigger driver information and warning messages. This approach facilitates graphical visualizations in vehicle-mounted displays or instrument clusters, audio cues and haptic feedback.

9 Infrastructure Integration / Communication Architecture

9.1 Compatibility with Integrated V2I Prototype

The V2I-SA project team planned to utilize existing test beds or test beds being built in Southeast Michigan with the CV RSU and interconnected back-office systems for testing in this project. The test beds could provide connectivity to test prototype CV equipment, applications and services. To maintain message compatibility and interoperability with the infrastructure already developed in other projects, the V2I Consortium met with FHWA and their contactors to coordinate development and testing plans. One location selected by the V2I-SA team for potential testing was the Integrated V2I Prototype (IVP) test bed setup at the intersection of 12 Mile and Telegraph Roads in the Detroit metropolitan area. The infrastructure at this location was configured to transmit SPaT and MAP messages to support the RLVW application developed in this project. In addition, the RSU was also configured to transmit RTCM v3.0 messages for GPS corrections.

The goal of utilizing the test bed location was to evaluate interoperability between the RSU built for the test bed and the test vehicles built in this project for RLVW. The intent was not to validate the test bed CV architecture but only to test successful decoding of the April 2015 version of SAE J2735 encoded SPaT, MAP, and RTCM message from the infrastructure.

As part of the preliminary testing efforts, the integrated vehicles were driven at this intersection and application data was collected to verify message compatibility and interoperability. However, messages broadcast by the RSU at this intersection could not be decoded correctly in the test vehicles due to an incompatibility with the message format implemented at the IVP test location. Given this circumstance, further testing at the 12 Mile and Telegraph intersection was not performed.

9.2 Portable Setup for Base Station for RTCM at Test Locations

This project used a RTCM-capable GPS receiver as the local base station to provide RTCM corrections. The base station needs to know its position accurately to generate RTCM corrections. When left powered with antenna under open sky for an extended period (at least 4 hours), the GPS receiver can calculate its absolute position. The base station can then start sending RTCM V3.0 corrections to the RSU, which in turn encodes it per J2735:2015-04 and broadcasts it.

9.3 Support for SPaT and MAP

The RSE broadcast SPaT and MAP to support the RLVW application only, since the CSW and RSZW/LC applications use map data which is embedded in the BIM. The RSE constructed these two messages such that the message ID links a MAP message from an intersection with a corresponding SPaT message, resulting in the pairing of the two messages.

Since the MAP message is static, it is broadcast at 1 Hz. Internally the RSU stores the information required to construct the MAP message in the form of an .xml file. This file format was chosen due to its grouping capabilities for items, which makes the items, sub-items and sub-sub-items of the SAE J2735 messages easy to implement.

The traffic signal controller provided the RSU with the signal phase and time information required to generate the SPaT message, hence in the absence of a traffic signal controller, SPaT is not generated. Because the SPaT message is dynamic, in that the content is constantly changing, it is broadcast every 100 ms.

10 Objective Test Procedures

This chapter describes the objective performance tests developed and executed to evaluate the three V2I safety applications, RLVW, CSW and RSZW/LC, against system performance requirements under controlled conditions. The testing efforts can be classified into two categories – preliminary on-road evaluation in Farmington Hills, Michigan near the Crash Avoidance Metrics Partners LLC (CAMP) facility and objective testing on a closed track in Fowlerville, Michigan.

Both in-vehicle and infrastructure-based system-level functionalities were validated using prototype vehicles and infrastructure. Factors such as road surface condition (dry or icy) and driving visibility (normal or reduced) were simulated in broadcast BIMs from an RSU for the CSW application to evaluate warning performance under simulated conditions. Multiple lane closures were incorporated to evaluate the performance of the RSZW/LC application. Various approach speeds and signal timings were used to evaluate the RLVW application. The timing (distance) of Inform and Warning messages was a key indicator used to assess the performance of the V2I safety applications.

Table 19 provides a high level summary of the different tests that were conducted.

Table 19: Summary of Tests Conducted

V2I Safety Application	Closed Track Testing in Fowlerville, MI	Preliminary Testing in Farmington Hills, MI	I2V Message	Passenger Vehicles (GM, Honda, Hyundai-Kia, Nissan, Subaru, VW)	Commercial Vehicle (Volvo Truck)	Number of Test Cases (Minimum 3 Runs/Test Case)
RLVW	✓	✓	SPaT / MAP / RTCM	✓	✓	10
CSW	✓	✓	BIM	✓	✓	6
RSZW/LC	✓	✓	BIM	✓	✓	5

Source: CAMP – V2I Consortium

Various test cases were designed and tested at various locations, including in a controlled environment, to validate applications and conduct performance measurements. For objective testing, ten test scenarios for RLVW on two- and four-lane intersections at various approach speeds were tested. Six test scenarios comprised of single- and dual-radii curves for CSW and five test scenarios at 45 mph and 70 mph for RSZW/LC were conducted.

10.1 Test Locations

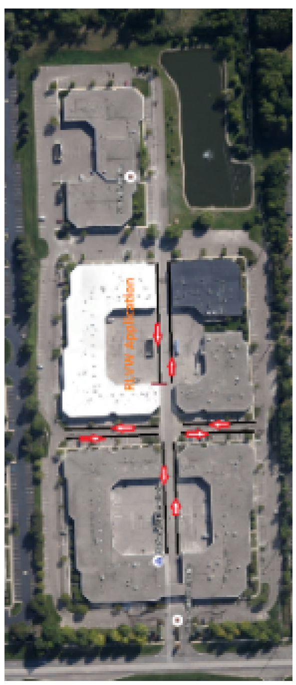
The preliminary testing was conducted in Farmington Hills, Michigan and at the FT Techno of America (FTTA) Fowlerville Proving Ground. The detailed objective test procedure evaluation was carried out at FTTA. Subsequent discussions and data analysis inspired further refinement to the safety algorithms that were validated at the University of Michigan's test facility.

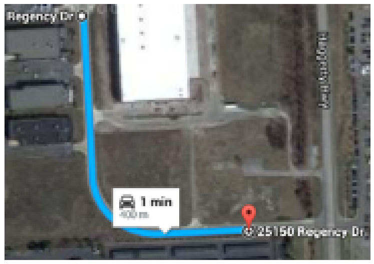
10.1.1 Preliminary Tests

Between September and November 2015, all three V2I safety applications were tested extensively around the CAMP campus in Farmington Hills to refine the implementation of the in-vehicle and infrastructure algorithms. CSW was tested at three sites (Regency Drive and M-5 and I-96 ramps) and RSZW was tested at one site (12 Mile Road, east of Haggerty Road). RLVW was tested within the CAMP campus using a traffic signal light and controller. The satellite images of the test sites, their descriptions, and key observations from the multiple rounds of testing are summarized in Table 20.

Note that preliminary versions of the algorithms, software and roadway configurations were tested here. This initial testing provided an opportunity to perform initial debugging and refinement of the system and led to revised versions of software later used in proving grounds for performance evaluations.

Table 20: Preliminary Tests Sites

V2I Safety Application	Location	Comments
		Site Description • Parking lot/driveway behind the CAMP office in Farmington Hills, MI
		CSW was tested near the CAMP campus on three curved roads. Site Descriptions • Regency Dr. in Farmington Hills, MI shown in (a). Curve radius = 40 m

V2I Safety Application	Location	Comments
	 (a)  (b)	• M-5 and I-96 ramps in Farmington Hills, MI shown in (b). Curve #1 (M-5) radius = 480 m and curve #2 (I-96) radius = 68 m
		Site Description • 12 Mile Rd, east of Haggerty Rd. in Farmington Hills, MI • Has a permanent lane closure • Created additional virtual lane closure • Speed limit 45 mph

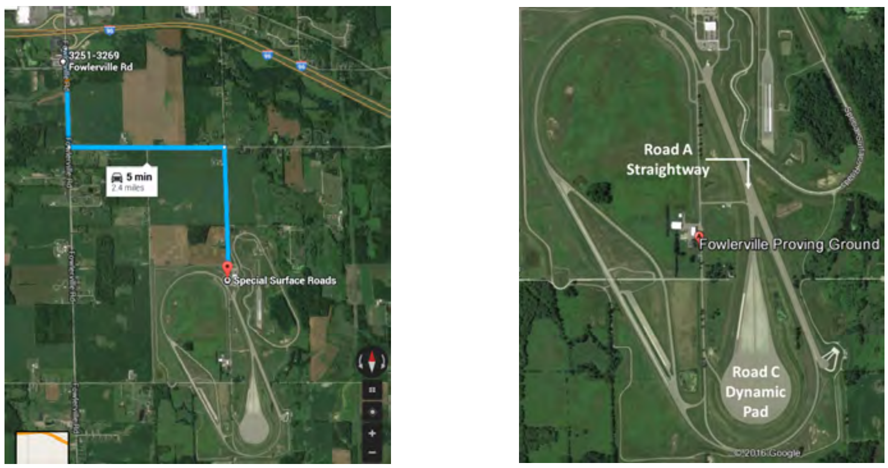
Source: Map images from Google. Used with permission. Text from CAMP – V2I Consortium

10.1.2 Testing in a Controlled Environment

This section describes the locations that were used for the controlled testing of the three safety applications. A comprehensive objective testing of the different functionalities was first carried out at the FTTA Proving Ground. Subsequently, further refinements were made to a RLVW and CSW safety application implementations that were validated at the test facility at the University of Michigan.

10.1.2.1 Testing at the FTTA Proving Ground

In November 2015 and February 2016, testing was performed using structured objective test procedures at the FTTA Proving Ground. This environment provided the opportunity to conduct repeated measures, including generating violations, for evaluation of all three V2I safety applications under controlled conditions. The FTTA Proving Ground is located approximately 2.5 miles from Interstate 96 (Exit Number 129). Open year-round, the facility can be rented in whole or part, with services and accommodations provided to suit customer needs and budget requirements. The facility has four test tracks, including a 4,500-foot straightaway, 48,000 square-feet of low- and middle-μ tiles, a 20-acre dynamic pad and a 3-mile oval track shown in Figure 47 below.



(a) (b)

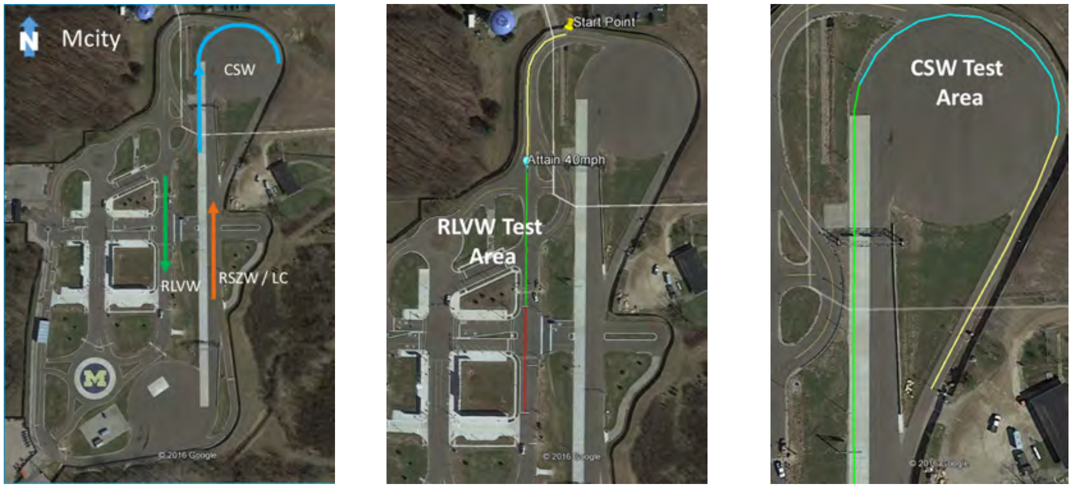
Source: ©2016 Google. Used with permission

Figure 47: Satellite Images of the FTTA Proving Ground – (a) Access to the Test Facility and (b) Layout of Test Tracks

The dynamic pad shown in Figure 47(b) facilitated creation of a layout of single- and dual-radii curvature for testing CSW. The same dynamic pad location was also used in creating a two-lane and a four-lane intersection with signal lights and controller for testing RLVW scenarios. The 1.2 km straightway was used for creating a work zone for testing reduced speed and multiple lane closures for RSZW/LC scenarios. The different parameters impacting driving speeds and safety such as visibility, road surface condition, superelevation, lane closures, and signal timing were simulated by altering the BIM and SPaT messages transmitted from portable infrastructure-installed RSU for testing.

10.1.2.2 Testing at the Test Facility at the University of Michigan

Between September and October 2016, additional tests were conducted at the University of Michigan test facility. The test facility is a 32-acre mock city and proving ground built for the testing of advanced transportation technologies, located on the University of Michigan North Campus in Ann Arbor, Michigan. The facility includes several familiar features of urban driving, including intersections, a railroad crossing, two roundabouts, brick and gravel roads, and parking spaces. This environment (shown in Figure 48) provided the opportunity to conduct repeated measures, including generating violations for evaluation of RLVW and CSW safety applications, under controlled conditions.



(a) (b) (c)

Source: © 2016 Google. Used with permission.

Figure 48: Satellite Images of the Test Facility at the University of Michigan and Test Areas for RLVW and CSW

10.2 Red Light Violation Warning

Ten test scenarios, shown in Table 21, were developed for the RLVW application. A description of the general requirements for conducting the tests is provided below. The specific test procedures are described in APPENDIX D. Any conditions that differ from those described here are addressed in the material devoted to the specific tests.

Table 21: RLVW Test Scenarios

Test	RLVW Test Scenarios
1	Reach intersection on red
2	Stop at intersection
3	Right turn on green
4	Multiple intersections within 300 m
5	Reach intersection when signal turns red
6	Reach intersection when signal turns green
7	Approach lane matching (edge of lane)
8	Right turn on red
9	Late lane change
10	Turn on yellow

Source: CAMP – V2I Consortium

10.2.1 General Test Requirements

The test was conducted in a closed test track with open sky environment. This is a validation test and no surrounding traffic was present when the test was active. The test track geometry accommodated the following regions:

- Setup Region – where the HV starts and accelerates to reach the required test speed
- Test Region – where the HV has reached the required test speed and is cruising towards the intersection, and receivers inform/warn
- Finish Region – where the HV comes to rest after completion of the test

10.2.2 Infrastructure Requirement

The infrastructure equipment was configured to transmit the following messages:

- Intersection MAP message at 1 Hz
- Intersection SPaT message at 10 Hz
- RTCM version 3.0 message types for high positioning performance near a base station. The technique is based on the use of carrier measurements and the transmission of corrections from the base station, whose location is well known, to the rover. In this case, the HV running the safety applications and using RTCM messages is the rover.
  - Message type 1001 – Global Positioning System (GPS) L1 observations at 5 Hz
  - Message type 1005 – Antenna Reference Point (ARP) station coordinates at 2 Hz

10.2.3 Information Collected During the Test

The following sets of log files were collected from each vehicle during the test:

- Scenario Record (SR) log file – The SR file is a binary file and can be “played back” on the On-Board Equipment (OBE) to recreate the scenario during post processing
- Application specific comma separated value (csv) log file – The application specific log file in text format contains all the information required to analyze the application performance

10.2.4 Test Documentation

An observer was inside the HV during the test. The observer monitored the position of the Driver Vehicle Interface (DVI) Inform/Warning message and documented the test results of each test run. The following items were documented for each test run.

Make and model of the test vehicle

- Test index
- Run index
- Time / Date
- Validity of the test run (Valid / Invalid)
- Results of the test run (Successful / Unsuccessful)

10.2.5 Test Evaluation – Pass and Fail Criteria

Each test was repeated nine times at speed of 55 mph, which was the primary speed for RLVW application testing. Time and weather permitting, the tests may also be conducted at speeds of 35 mph and 70 mph. A test run was considered successful when a warning is provided to the driver within specified warning distance (between Flag 3 and Flag 4). The test was considered a "Pass" when 7 out of 9 valid test runs are successful. Otherwise the test is considered a "Fail."

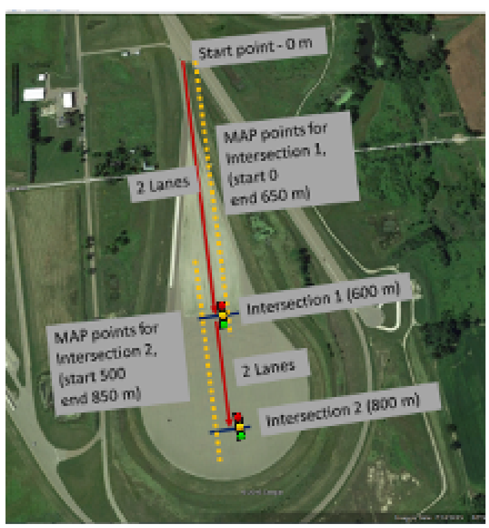
10.2.6 Test Layout

In the following section test layouts for various test scenarios are described. The following flags were placed on the test road for all tests.

- Flag 1 to indicate the HV start point from stationary position
- Flag 2 to indicate the HV has attained the specified speed and cruise control is engaged
- Flags 3 and 4 to indicate locations at which expected warning is generated

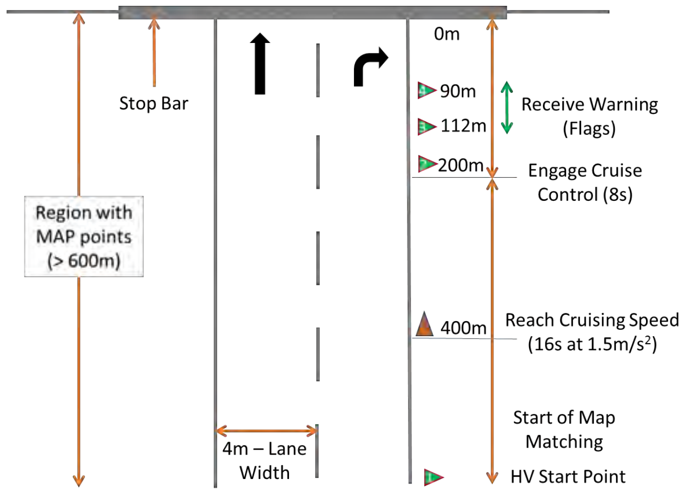
10.2.7 Test Layout for Two-Lane Scenario

Figure 49 describes the test layout for the two-lane test scenarios with two intersections 200 m apart. In all, 11 test cases were developed for testing the RLVW application. These tests are described in more detail in the following subsections. The first intersection was set up at 600 m from the HV start point. This test layout was used for Tests 1 through 6, 9 and 10. Test 4 was designed to use both intersections, while other tests were designed to be conducted at the first intersection. Figure 50 describes the layout for flag placement for these tests. Figure 51 describes SPaT information used for Tests 1 through 6, and 9. Figure 52 describes the SPaT information for Test 10.



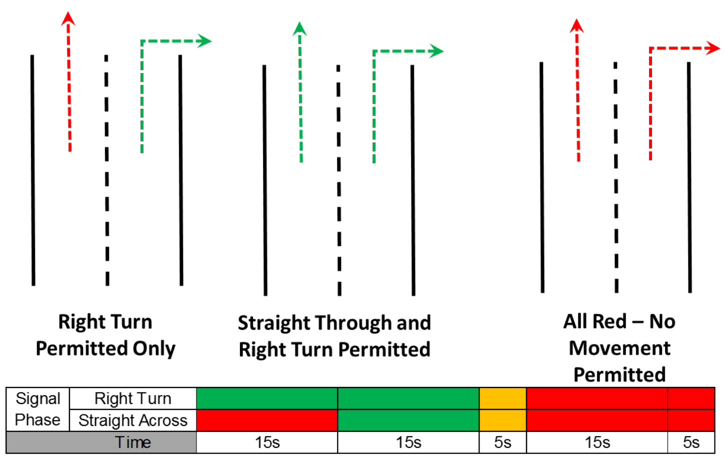
Source: Map images from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 49: Layout for Two-Lane Scenario



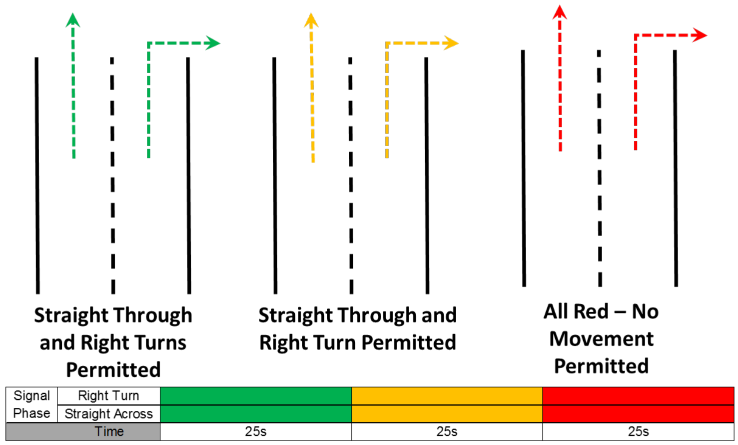
Source: CAMP – V2I Consortium

Figure 50: Flag Placement for Two-Lane Scenario – 55 mph Approach Speed



Source: CAMP – V2I Consortium

Figure 51: SPaT for Tests 1 Through 6 and 9



Source: CAMP – V2I Consortium

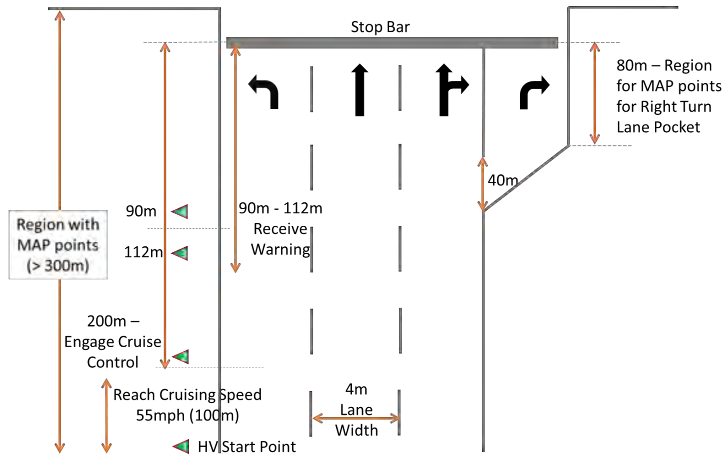
Figure 52: SPaT for Test 10

10.2.8 Test Layout for Four-Lane Scenario

Figure 53 describes the test layout for the four-lane intersection test scenarios which includes Test 4. Figure 54 describes the flag placement for the test. Figure 55 describes the SPaT information for Tests 7 and 8.

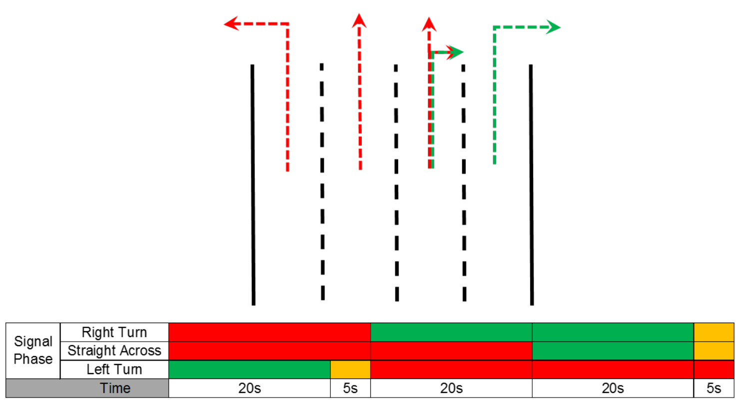
Source: Map images from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 53: Layout for Four-Lane Intersection Scenario



Source: CAMP – V2I Consortium

Figure 54: Flag Placement for Four-Lane Scenario – 55 mph Approach Speed



Source: CAMP – V2I Consortium

Figure 55: SPaT for Tests 7 and 8

10.3 Curve Speed Warning

Six test scenarios for the CSW application were developed for the tests. These are listed in Table 22 and presented in detail in APPENDIX E. All tests were conducted on asphalt road on a flat surface, however, a 5˚ superelevation is specified in the BIM to simulate real-world curvature with superelevation. Tests 1 through 4 are designed for a single-radius curve under different speeds, road conditions and visibility conditions. Tests 5 and 6 are designed for a dual-radii curve that transitions from a large radius to a small radius, for validating application performance.

Table 22: CSW Test Scenarios

Test	Approach Speed	Minimum Radius of Curvature	Surface Condition	Visibility
1	55	100	Dry	Normal
2	35	100	Dry	Normal

Test	Approach Speed	Minimum Radius of Curvature	Surface Condition	Visibility
3	55	100	Icy	Normal
4	55	100	Dry	Reduced
5	45	100 and 50	Dry	Normal
6	45	100 and 50	Icy	Normal

Source: CAMP – V2I Consortium

A description of the general requirements for conducting the tests is provided in Subsections 10.3.1 through 10.3.5. Any specific requirements that differ from the general requirements are addressed in the subsections devoted to specific tests.

10.3.1 General Test Requirements

The test was conducted in a closed test track with open sky environment. This is a validation test and no surrounding traffic was present when the test is active.

The relevant geometry of this test consisted of single- and double-radii curves of 100 m (and 50 m contiguous curve). To achieve the target Approach Speed, a 540-m straight roadway section was utilized before the curve.

An RSU was placed at the test location and programmed to broadcast the CSW event parameters such as curve geometry, road surface material, road surface condition, and superelevation in the BIM.

10.3.2 Recorded Data Element

The following data elements were logged for each test run at a frequency of 10 Hz

- Map matching status
- Inform / Warning status (Inform, Warning 1, Warning 2)
- Received BIM contents
    - Minimum radius
    - Road material
    - Road condition
    - Banking angle
    - Friction coefficient
    - Posted and advisory speed limits
- Algorithm output
    - Minimum Radius, Centripetal V_{max}, Stability V_{max}, Adopted V_{max}
    - Distances for Inform, Warning 1 and Warning 2, Target Node number
- HV Speed

- HV GPS Location

10.3.3 Test Documentation

An observer was inside the HV during the test. The observer monitored the position of the DVI Inform/Warning message generation at the specified flag locations and documented the test results of each test run (successful/unsuccessful). The following data was documented for each test run:

- Test index
- Run index
- Make and model of the test vehicle
- Time/Date
- Validity of the test run (Valid/Invalid)
- Results of the test run (Pass/Fail)

10.3.4 Test Setup and Layout – Single Radius Curve

Layout for conducting Tests 1 through 4 is shown in Figure 56. The layout is defined for a single fixed-radius curve to represent a typical freeway exit ramp. An RSU is placed at the test location which broadcasts the CSW event parameters in BIM.

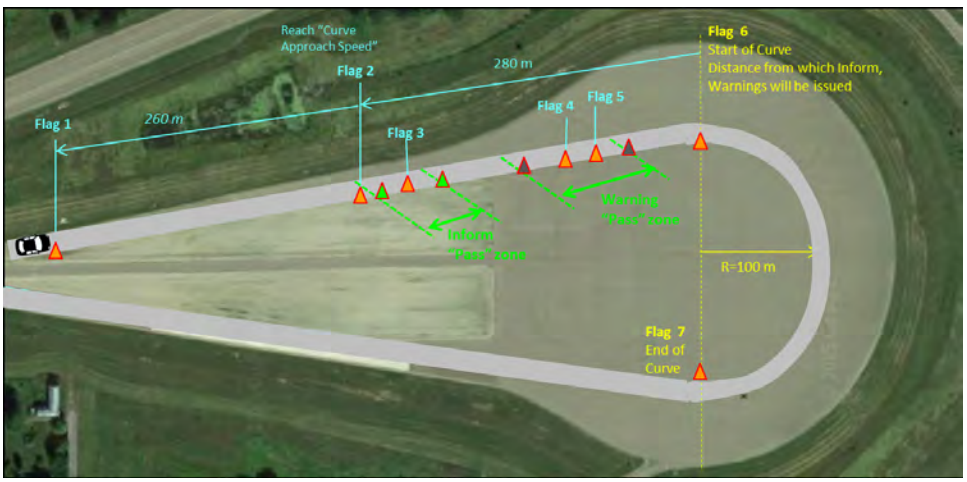


Figure 56: Test Layout for Tests 1 Through 4

10.3.5 Test Evaluation – Pass and Fail Criteria

Any differences in Pass/Fail criteria are described in the appropriate Test sections below.

A run is considered successful in this test if:

- An Inform message generation occurs in the "Inform Pass Zone"
- Warnings 1 and 2 generation occur in the "Warning Pass Zone"

The test is considered a “Pass” if at least 4 out of 6 valid iterations are successful. Otherwise the test is considered a “Fail.”

10.4 Reduced Speed Zone / Lane Closure Warning

Five test scenarios, each at two different approach speeds, shown in Table 23 were developed for the test. These are presented in detail in APPENDIX F. A description of the general requirements for conducting the tests is provided in Subsection 10.4.1. Any specific requirements that differ from the general requirements are addressed in the material devoted to specific tests.

Table 23: RSZW/LC Test Scenarios

Test	Test Scenarios	Approach Speeds (mph)
1	Reduced speed test • Workers not present	70 / 45
2	Reduced speed test • Workers present	70 / 45
3	One-lane closure test • Lane #3 closed • No reduced speed test	70 / 45
4	Two-lane closure test • Lane #3 and #2 closed • Turn signal indication for lane change	70 / 45
5	Two-lane closures and reduced speed test • Lanes #3 and #2 closed • Turn signal indication for lane change • Reduced speed test o Workers present	70 / 45

Source: CAMP – V2I Consortium

10.4.1 General Test Requirements

The test was conducted in a closed test track with open sky environment. This is a validation test and no surrounding traffic was present when the test is active.

The test track geometry accommodated the following additional spaces:

- Space before the traffic lane for the HV to reach the test Approach Speed
- Space within the reduced speed zone for the HV to continue driving for a while to see if it receives Inform/Warning message while in the zone
- Space after the end of the reduced zone for the HV to break and reach full stop

10.4.2 Infrastructure Requirement

The RSU transmits BIM with the reduced speed zone information every second. Optionally, RTCM 1001 and RTCM 1005 are also transmitted for enhancing positional accuracy.

10.4.3 Recorded Data Element

The following data elements were logged for each test run:

- DVI status (Inform/Warning) at a frequency of 10 Hz
- Distance from the beginning of reduced speed zone at a frequency of 10 Hz
- Distance from the end of reduced speed zone at a frequency of 10 Hz
- HV speed at a frequency of 10 Hz
- HV longitudinal acceleration at a frequency of 10 Hz
- HV brake status at a frequency of 10 Hz
- HV turn signal status at a frequency of 10 Hz
- GPS trace for HV
- Number of satellites and Horizontal Dilution of Precision (HDOP) as calculated by the GPS receiver
- Correction status (bit value)
- RTCM messages received status at a frequency of 10 Hz
- BIM received

10.4.4 Test Documentation

Photographs of the test track including flags were taken and documented. An observer was inside the HV during the test. The observer monitored the position of the DVI Inform/Warning message and documented the test results of each test run (successful/unsuccessful). The following items were documented for each test run

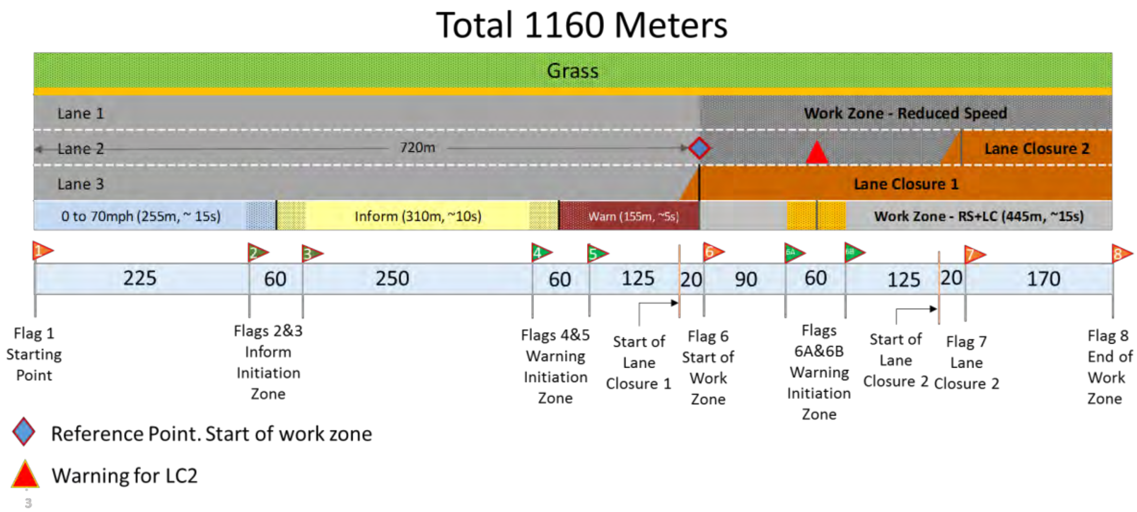
- Make and model of the test vehicle
- Test index
- Run index
- Time/Date
- Validity of the test run (Valid/Invalid)
- Results of the test run (Successful/Unsuccessful)

10.4.5 Test Layout

Test layouts for 70 mph and 45 mph approach speeds are described in the following subsections.

10.4.5.1 Approach Speed 70 mph

Figure 57 and Table 24 describe the test layout for all test scenarios for 70 mph Approach Speed. Lane 1 was used for the reduced speed tests without lane closures, while Lane 3 and Lane 2 were used for single- and double-lane closure tests respectively.



Source: CAMP – V2I Consortium

Figure 57: Test Layout for 70 mph Approach Speed

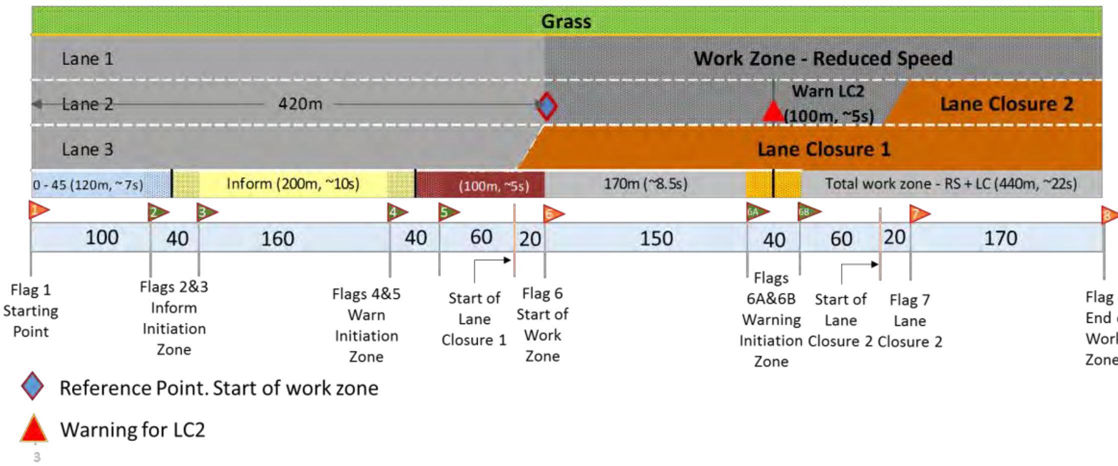
Table 24: Flag Locations for 70 mph Approach Speed

Flag Locations	#1	#2	#3	#4	#5	LC1	Ref / #6	#6A	#6B	LC2 / #7	#8
Dist. (m) from Ref.	-720	-495	-435	-185	-125	-20	0	+40	+150	+275	+445

Source: CAMP – V2I Consortium

10.4.5.2 Approach Speed 45 mph

Figure 58 and Table 25 describe the test layout for all test scenarios for 45 mph Approach Speed. Lane 1 was used for the reduced-speed tests without lane closures, while Lane 3 and Lane 2 were used for single- and double-lane closure tests respectively.



Source: CAMP – V2I Consortium

Figure 58: Test Layout for 45 mph Approach Speed

Table 25: Flag Locations for 45 mph Approach Speed

Flag Locations	#1	#2	#3	#4	#5	LC1	Ref / #6	#6A	#6B	LC2 / #7	#8
Dist. (m) from Ref.	-420	-320	-280	-120	-80	-20	0	+150	+190	+250	+440

Source: CAMP – V2I Consortium

10.4.6 Required Tests Performed

There are five test scenarios as listed in Table 23. Each test scenario was conducted at two different speeds for performance measurement and to confirm that the application performed as intended at various speeds.

Tests 1 through 5 were carried out at Approach Speed of 70 mph and Tests 6 through 10 were carried out at Approach Speed of 45 mph. Each test scenario is explained in further detail in APPENDIX F. Test goals and the test setup are provided for each test scenario. The heavy-duty truck performed only at the lower Approach Speed. The higher Approach Speed (e.g., 70 mph) was not attainable in the available launch segment of the test track.

10.4.7 Test Evaluation – Pass and Fail Criteria

A test run is considered successful when the Inform and/or Warning messages are generated in specified inform and warning zones. The test is considered “Pass” if at least 7 out of 9 valid test runs are successful. Otherwise the test is considered “Fail.”

The Reduced Speed algorithm in the RSZW/LC application integrates two speed thresholds for the vehicle speed for generating Warning. The default value for upper threshold speed is set to work zone speed limit +7 mph and for lower threshold speed is set to work zone speed limit +4 mph.

11 Results and Analysis of Objective Tests

The results of performing the OTP for each of the V2I safety applications are described in this section.

11.1 RLVW Test Results and Analysis

Table 26 summarizes the result of RLVW test cases. The tests highlighted in green are the ones that passed the evaluation criteria, and the ones in beige failed the criteria. It was observed that during some runs the test did not start at the appropriate signal phase/time as planned for the test, and hence did not produce the expected outcome. These runs were not included in the evaluation criteria. All tests were conducted at the primary test speed – 55 mph. Additional speed tests – 35 mph and 70 mph – were not conducted due to time constraints. Similarly, due to time constraints, four tests were conducted with six runs instead of the scheduled nine runs.

Table 26: RLVW Test Summary

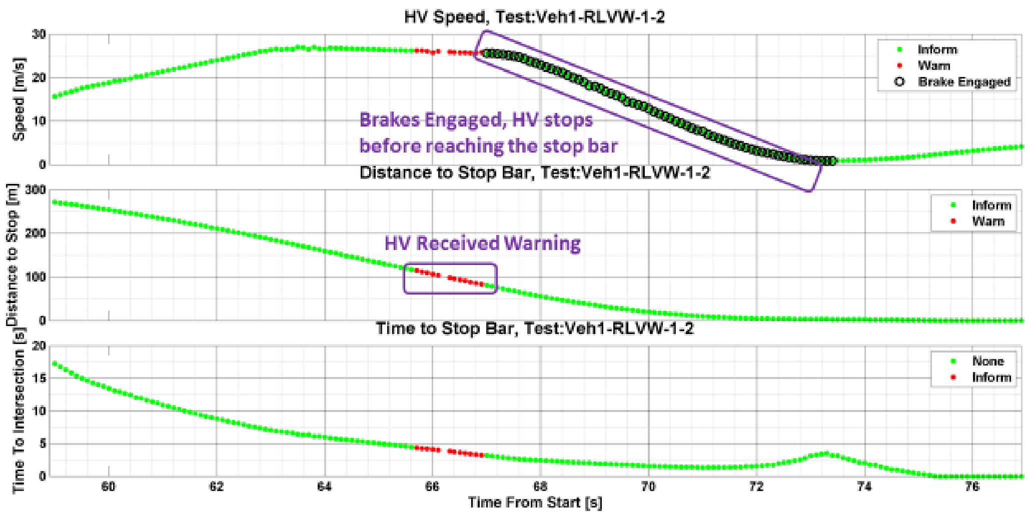
Test #	Test Scenario	Runs per Vehicle	# of Vehicles	Total Runs	Successful Runs	Comments
1	Reach intersection on red	3	3	9	7	
2	Stop at intersection	3	3	9	6	Test start time – signal phase synchronization issue with three runs
3	Right turn on green	3	3	9	8	Test start time – signal phase synchronization issue with one run
4	Multiple intersections within 300 m	6	2	12	12	
5	Reach intersection when signal turns red	3	3	9	6	Test start time – signal phase synchronization issue with three runs
6	Reach intersection when signal turns green	3	3	9	0	See 6.1.6
7	Approach lane matching	3	2	6	0	See 6.1.7
8	Right turn on red	3	2	6	3	Right turn with brake suppressed the Warning
9	Late lane change	3	2	6	6	
10	Turn on yellow	3	2	6	6	

Source: CAMP – V2I Consortium

11.1.1 Test 1: Reach Intersection on Red

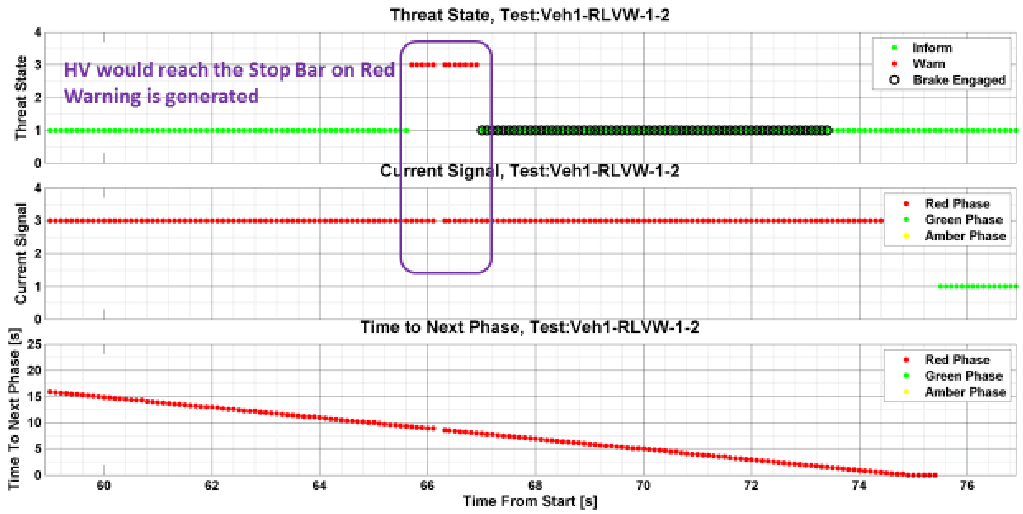
This test is intended to validate true positive Warning at an appropriate distance from the stop bar on a traffic lane with straight only maneuvers. As shown in Figure 59, the HV approaches an intersection when signal phase is red, and is at the risk of running the red light. A Warning is generated with sufficient time for the driver to stop before reaching the stop bar of the intersection.

Figure 60 shows the summary of Test 1, and indicates the observed warning distance from the stop bar as a percent of the calculated warning distance from the stop bar at a given speed. As indicated in the test plan, the criteria for a successful test was to receive the Warning between 90% to 110% of the Calculated Distance from the stop bar. Figure 61 indicates that all test runs met this criterion.



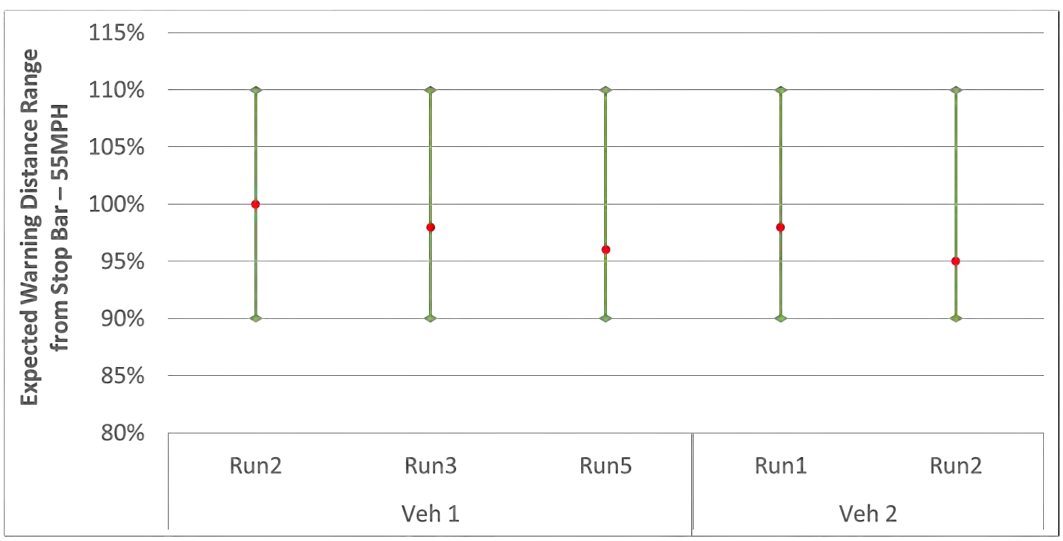
Source: CAMP – V2I Consortium

Figure 59: RLVW Test 1 – Warning and Distance to Stop Bar



Source: CAMP – V2I Consortium

Figure 60: RLVW Test 1 – Warning State and Current Signal Phase

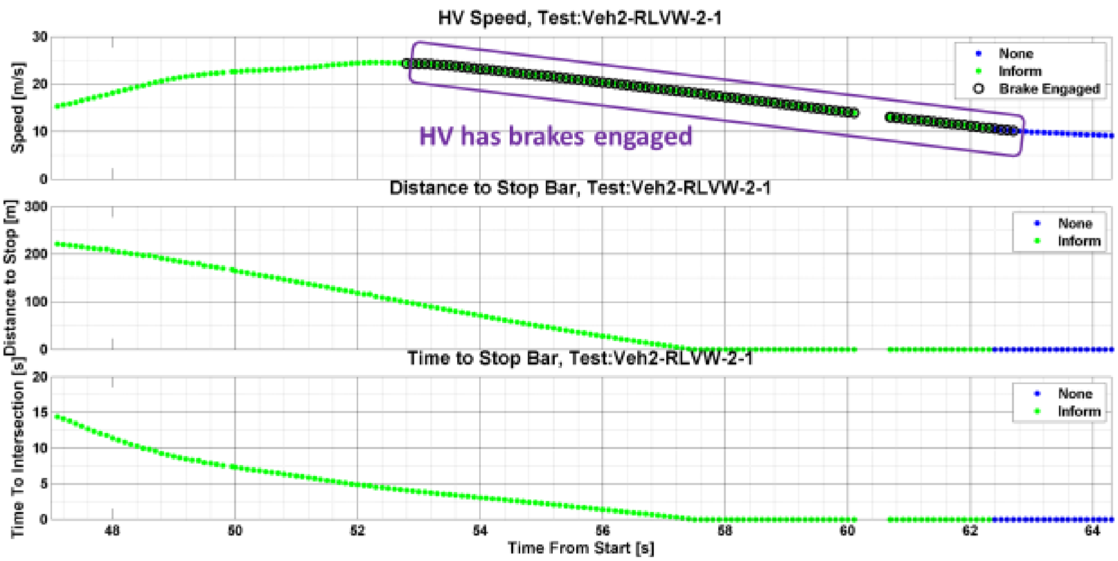


Source: CAMP – V2I Consortium

Figure 61: Summary of RLVW Test 1

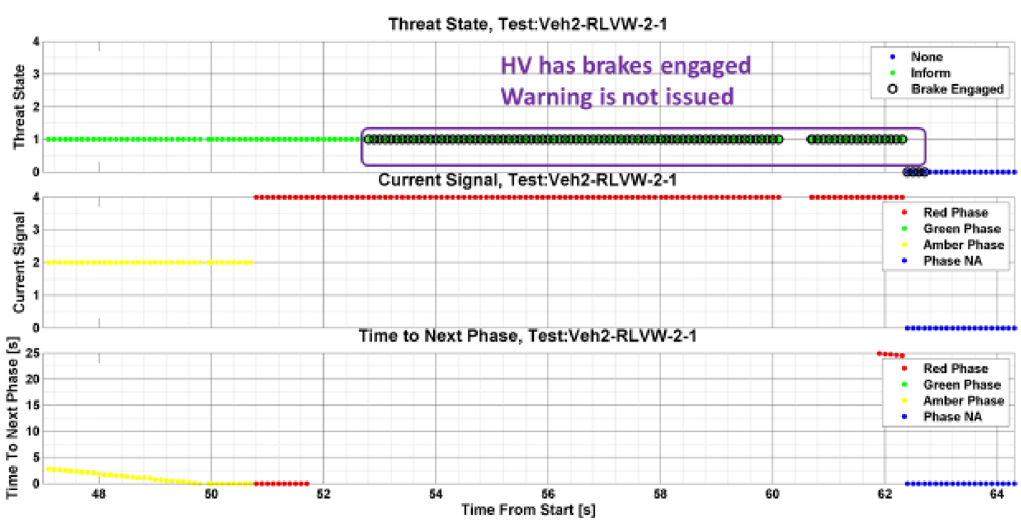
11.1.2 Test 2: Stop at Intersection

This test is intended to test true negative Warning (meaning no Warning), where an HV approaches an intersection on red, and applies the brake with an intention to have a full stop at the stop bar on a traffic lane with straight only maneuvers. As seen in Figure 62 and Figure 63, the HV approaches the intersection on red signal phase, has its brakes engaged and comes to a full stop at the stop bar. The Warning is suppressed.



Source: CAMP – V2I Consortium

Figure 62: RLVW Test 2 – Warning and Distance to Stop Bar, with Brake Status



Source: CAMP – V2I Consortium

Figure 63: RLVW Test 2 – Warning State and Current Signal Phase, with Brake Status

11.1.3 Test 3: Right Turn on Green

The main goal of this test is to validate that the RLVW system suppresses the Warning generation when the driver makes a lane change from a lane which has a red signal phase (Warning should be generated if the driver continues on this lane) to a lane which has green signal phase. It was observed that Warnings were suppressed for all the Test 3 runs.

11.1.4 Test 4: Multiple Intersections within 300 m

This test is intended to validate the implementation of the relevance algorithm. This test involves two intersections as shown in Source: CAMP – V2I Consortium

Figure 128. The SPaT for the primary intersection (Intersection 1) is the same as that in Tests 1 through 3. However, the signal phase for both the lanes at the second intersection is always set to red.

Runs 1 through 3 were conducted such that the HV reaches the first intersection on green signal phase and no Warning is generated; the HV reaches the second intersection on red signal phase, and a Warning is generated

Runs 4 through 6 were conducted such that the HV reaches both of the second intersections on red signal phase, and a Warning is generated.

The relevance algorithm performed as expected, and the outcomes can be seen in Figure 64.

Source: CAMP – V2I Consortium

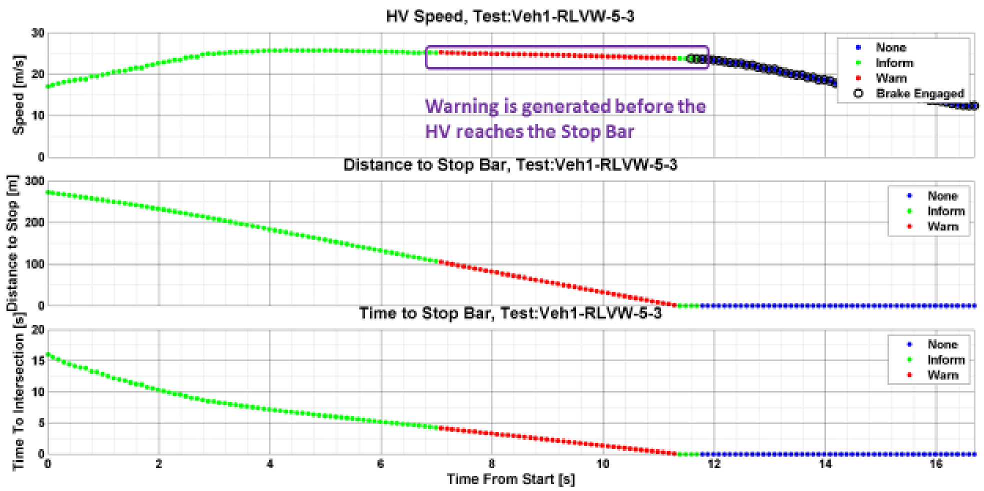
Figure 64: Summary of RLVW Test 4

11.1.5 Test 5: Reach Intersection When Signal Turns Red

This test is intended to verify that a Warning will be generated when the signal phase changes to red just prior to the HV reaching the stop bar. In this test the HV approaches the intersection while the signal phase is green. The test was executed such that the signal phase changes to red just prior to the HV reaching the stop bar. As seen in Figure 65 and Figure 66, a Warning was generated when the signal phase was yellow, indicating that the signal phase would change to red by the time the HV reaches the stop bar.

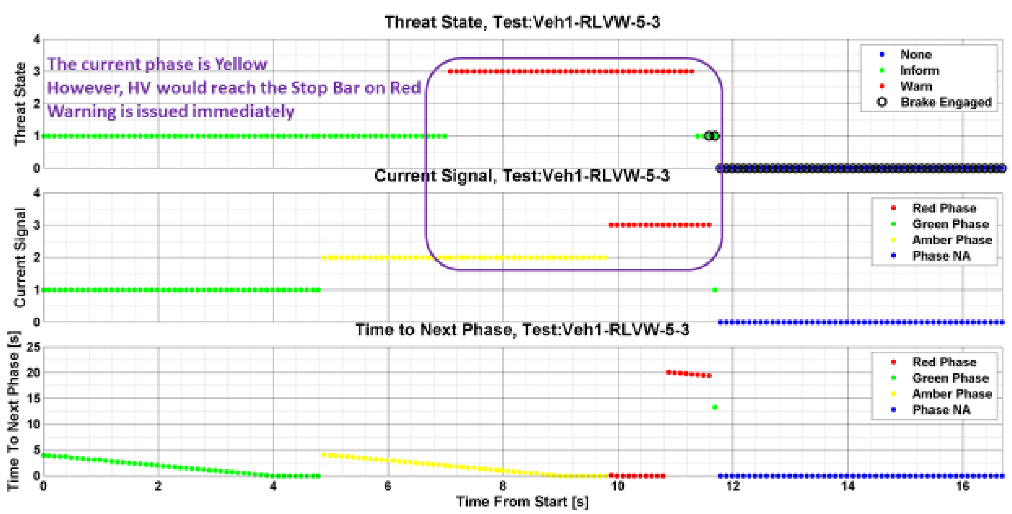
Figure 67 shows the summary of Test 5, and indicates the observed warning distance from the stop bar as a percent of the calculated warning distance from the stop bar at a given speed. As indicated in the test plan, the criteria for a successful test was to receive the Warning between 90% to 110% of the Calculated Distance from the stop bar. Figure 66 indicates that all test runs meet this criterion.

Note: This test required the HV to reach the stop bar with in a small window of time (the transition from yellow to red signal phase). As a result, the number of runs for this test is fewer in comparison to other tests.



Source: CAMP – V2I Consortium

Figure 65: RLVW Test 5 – Warning and Distance to Stop Bar, with Brake Status



Source: CAMP – V2I Consortium

Figure 66: RLVW Test 5 – Warning State and Current Signal Phase, with Brake Status

Source: CAMP – V2I Consortium

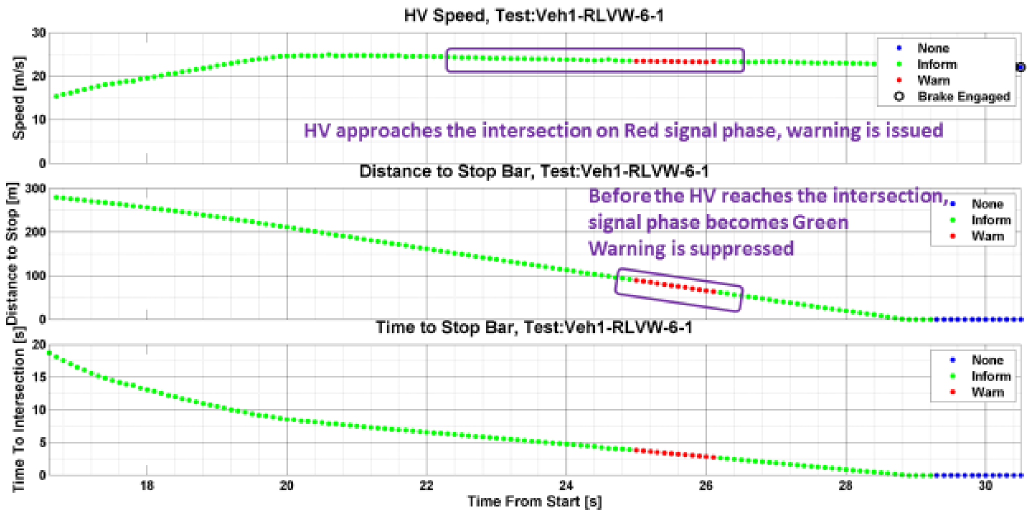
Figure 67: Summary of RLVW Test 5

11.1.6 Test 6: Reach Intersection When Signal Turns Green

This test is intended to validate the suppression of the Warning message when the HV approaches the intersection at the start of the green phase. It can be seen in Figure 67, Figure 68 and Figure 69 that the test was conducted such that the signal phase is red when the HV approaches the intersection, and changes to green just before the HV reaches the intersection. The current algorithm implementation generates a Warning when the HV approaching the intersection reaches the Warning Zone and signal phase is red. However, since the HV already has the SPaT information, two scenarios exist:

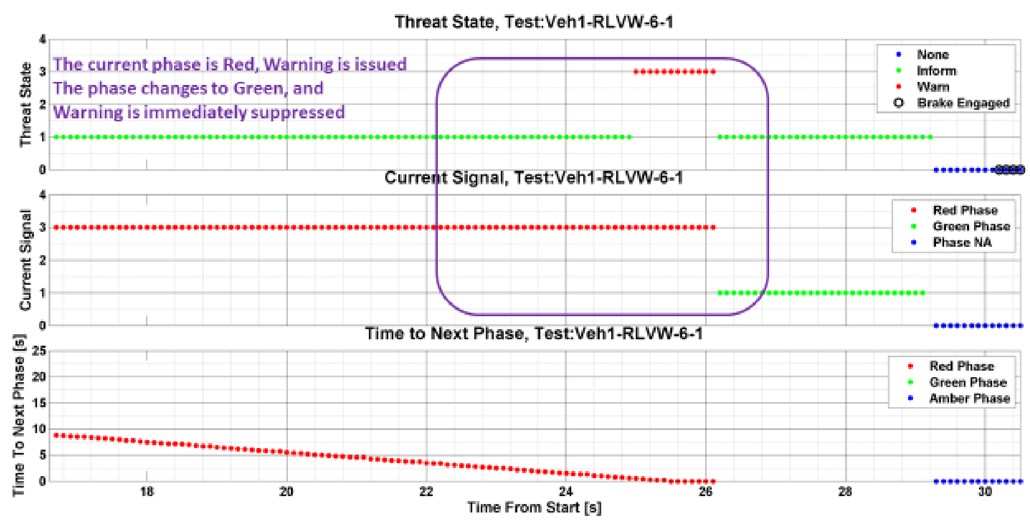
- The Warning could be suppressed if the HV maintains its current speed and could reach the intersection by the time the signal phase has turned green, avoiding a false positive
- A late Warning or violation could occur if the vehicle maintains the current speed until it is close to the intersection and HV speed is then increased

Given the possibility of a late Warning that does not provide enough time for the driver to take an appropriate action or worse, violation may occur, the Technical Team has taken a conservative approach and considered generating the Warning as shown in Figure 70. It is also left open for implementation by an individual OEM.



Source: CAMP – V2I Consortium

Figure 68: RLVW Test 6 – Warning and Distance to Stop Bar, with Brake Status



Source: CAMP – V2I Consortium

Figure 69: RLVW Test 6 – Warning State and Current Signal Phase, with Brake Status

Source: CAMP – V2I Consortium

Figure 70: Summary of RLVW Test 6

11.1.7 Test 7: Approach Lane Matching (Edge of Lane)

This test is intended to validate the lane matching using turn prediction based on driver intent for an HV driven on the edge of an approach lane when lane-level determination is uncertain. In this test case, a lane is associated with two signal phases and thus two permissible movements – straight through the intersection and a right turn. The “turn prediction” logic uses additional input from vehicle turn signal indicator status to determine proper lane from driver intent and associate with proper signal phase. The test could not be performed successfully since vehicle GPS performed very well (without RTCM correction) under the open sky test location and lane-level determination could not be forced as uncertain and thus could not invoke the logic for “turn prediction” logic in the application.

In the current implementation, once the map matching identifies the lane and associates with the signal phase, it does not re-associate with a different phase when the vehicle turn indicator is activated/de-activated. The application needs to be refined to appropriately re-associate lane position based also on turn indicator status.

11.1.8 Test 8: Right Turn on Red

This test is intended to validate Warning suppression for right turn after stop at the stop bar on a traffic lane with straight and right turn maneuvers allowed. In this test, the signal phase is red as the HV approaches and reaches the stop bar.

This test is conducted in two different ways:

- Vehicle 1: As the HV approached the intersection, the vehicle operator did not engage the brake, and tried to decelerate naturally before making the right turn. In this case, the deceleration was not sufficient; hence as seen in Figure 71, Warning was generated for all test runs.
- Vehicle 2: As the HV approached the intersection, the vehicle operator engaged the brake and came to a rolling stop before making the right turn. In this case, due to the deceleration, Warning was suppressed for all test runs.

Source: CAMP – V2I Consortium

Figure 71: Summary of RLVW Test 8

11.1.9 Test 9: Late Lane Change

The main goal of this test is to validate that the RLVW system suppresses the Warning generation when the driver makes a late lane change from a lane which has red signal phase (Warning should be generated if the driver continues on the current lane), to a lane which has green signal phase. This test is similar to Test 3, with the difference that the HV makes a very late lane change. Similar to Test 3, Warnings were suppressed for all the Test 9 runs.

11.1.10 Test 10: Turn on Yellow

The main goal of this test is to validate that the RLVW system suppresses the Warning generation when the HV approaches the intersection and reaches the stop bar on a yellow signal phase. As expected, Warnings were suppressed for runs conducted for Test 10.

11.1.11 Analysis of Additional RLVW Tests Conducted at the Test Facility at the University of Michigan

The following subsection provides the analysis for the tests conducted at the test facility at the University of Michigan. The test layout, signal phase and timing information and scenario description are provided in APPENDIX D, Section D.11. As Figure 135 in the appendix, the permissible movement on lane 1 (the left lane) is for through movement only. The permissible movements on lane 2 (right lane) are through movement and right turn. The purpose of these tests was to assess performance of the turn prediction algorithm by taking into consideration the vehicle's turn signal status for the lane that permits multiple movements such as going straight and right turn at an intersection.

This section contains two types of graphs for the test result analysis. The first type contains three sub-charts that describe the HV's lane association, movement direction associated with signal phase and vehicle turn signal status indicator. Left of the vertical blue dashed line, the chart indicates the HV approaching the intersection and right of the blue dashed line indicates the HV has crossed the intersection and the application algorithm has ended. The lane indicator value goes to zero. For example, as shown in top chart in Figure 72, the HV is associated with lane number 2 (right lane) from the start of the test, and continues on lane 2 as it approaches the intersection. Once the HV has crossed the intersection, the lane number goes to 0 and the application algorithm has ended.

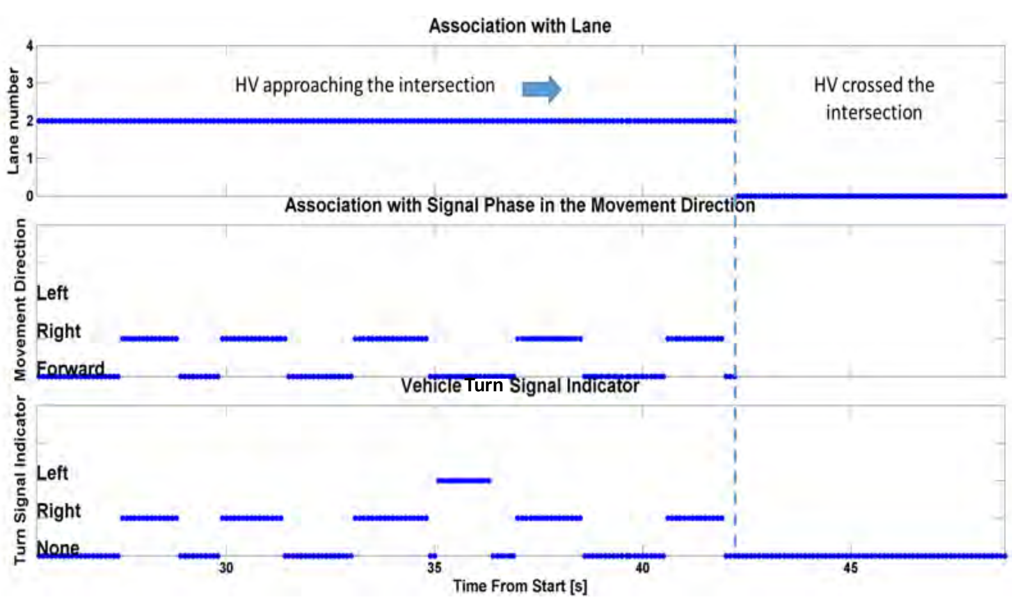
The center chart in the graph indicates the HV's association with the signal phase in its predicted movement direction, considering HV's turn signal status. In the chart, it is indicted by Forward for straight through, and Right and Left for right or left, respectively. The bottom chart in the graph indicates status of the HV's turn signal indicator.

The second graph type contains three sub-charts. For example, as shown in Figure 74, the top chart shows threat state generated by the RLVW application indicated as None, Inform and Warn shown by the legend in the graph. Additionally, instances where vehicle brake is engaged is shown. The center chart shows the current signal phase in the HV's lane and the direction of movement. The bottom chart shows the time to next signal phase in the HV's lane and permissible movement direction.

11.1.11.1 Lane and Signal Phase Association Validation Test

This test is intended to validate appropriate association of the HV's lane with signal phase in the RLVW application. As shown in the top chart of Figure 72, the HV is approaching the intersection on Lane 2. The center chart of Figure 72 shows the movement direction that the algorithm associates the HV with, and the bottom chart of Figure 72Source: CAMP – V2I Consortium

Figure 72 shows the HV's turn signal indicator status. When a turn signal indicator is not activated, the application associates the HV's position to the through movement signal phase on the lane. When the right turn signal indicator is activated, the application appropriately associates the HV with the right turn signal phase on the same lane. It can also be noticed that since left turn is not permitted on lane 2, when HV's left turn signal indicator is on, the algorithm associates the HV with the through movement on the same lane.

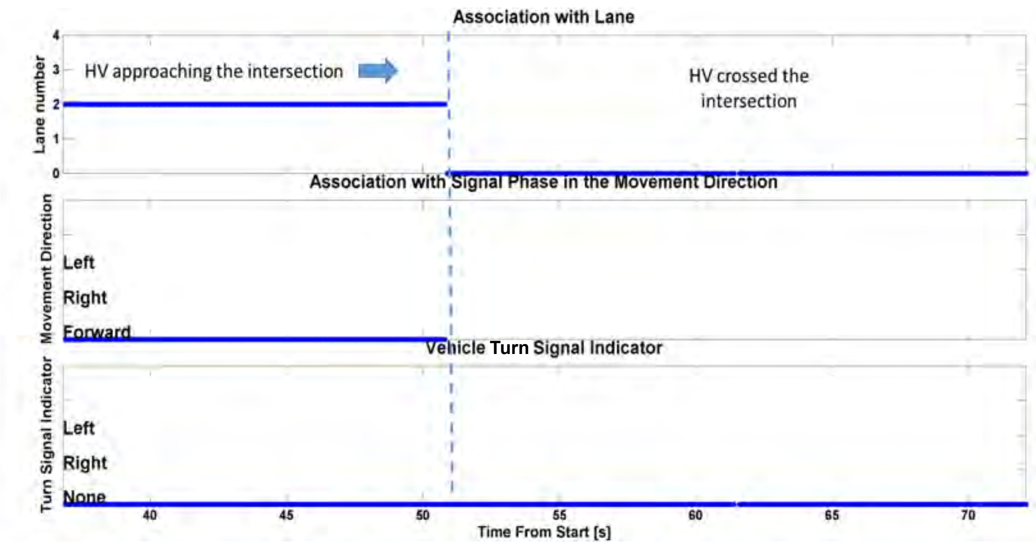


Source: CAMP – V2I Consortium

Figure 72: Lane and Signal Phase Association Validation Test

11.1.11.2 Application Validation – Right Turn Signal Indicator Not Activated

This test is intended to validate appropriate association of the HV's lane with signal phase in the RLVW application. As shown in the top chart of Figure 73, the HV is approaching the intersection on Lane 2. The center chart of Figure 73 shows the movement direction that the algorithm associates the HV with, and the bottom chart of Figure 73 shows the HV's turn signal indicator status. When a turn signal indicator is not activated, the application associates the HV's position to the through movement signal phase for the lane.

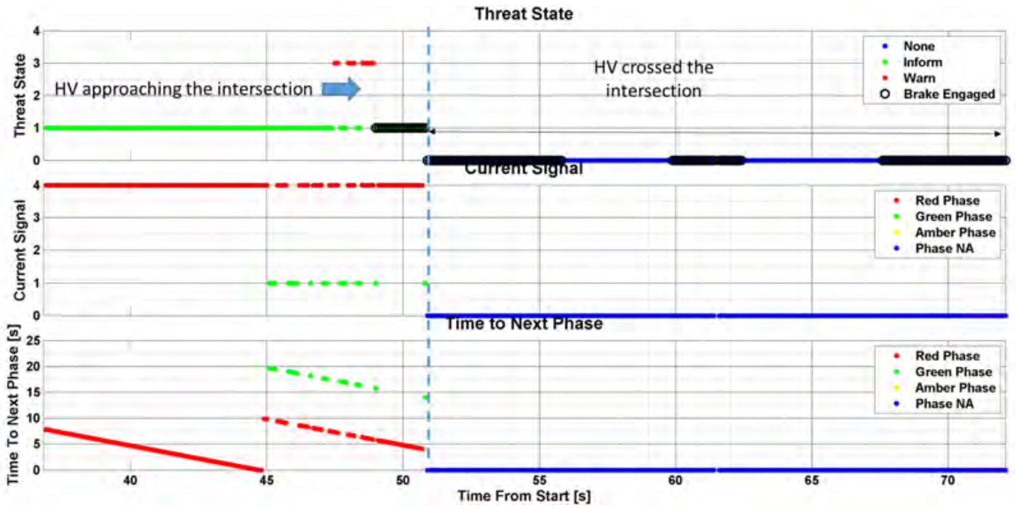


Source: CAMP – V2I Consortium

Figure 73: Application Validation – Right Turn Signal Indicator NOT Activated

As the HV approaches the intersection, it can be seen from the center chart of the Figure 44, that the signal phase for the through movement is red. Hence the RLVW application generates a Warning as shown in the top chart of Figure 74.

It can be noted from the center chart of Figure 74 that the association of current signal phase for straight through versus right turn for the lane toggles between green and red. The turn prediction algorithm, in addition to using the status of turn signal indicator, also uses vehicle acceleration and deceleration values to predict driver intent. In the absence of turn signal indicator activation (left/right), if the vehicle is decelerating, the algorithm predicts the driver is slowing down for a red signal light. Therefore, it associates the straight lane with red signal phase. Whereas, if and when the vehicle is accelerating the algorithm assumes the driver's intent is to go through the green/yellow signal light and looks for a straight through lane, and if not found, looks for any lane with a green/yellow phase, which in this test case is a right turn lane. Hence the algorithm predicts that the driver intends to make a right turn.



Source: CAMP – V2I Consortium

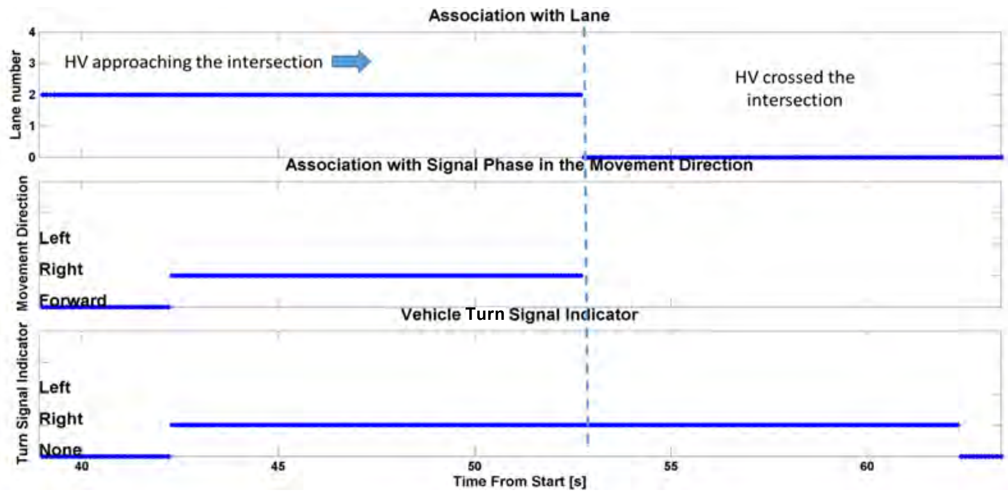
Figure 74: Warning Status – Right Turn Signal Indicator NOT Activated

The current algorithm does not have set threshold limits for acceleration/deceleration. When the vehicle speed has a very slight variation, causing change in acceleration/deceleration due to coasting or other condition, prediction for driver intent in the absence of turn signal activation is based on vehicle acceleration/deceleration and it keeps toggling association between red and green/yellow phase. This can be prevented by strengthening the algorithm by introducing small hysteresis in detected change in acceleration/deceleration. The algorithm will be further refined to include hysteresis to minimize undesirable lane toggling using following approach:

- Consider the vehicle is accelerating
- If the vehicle's acceleration value is less than a configurable deceleration threshold, the vehicle is considered decelerating
- If the vehicle's acceleration value is greater than a configurable acceleration threshold, the vehicle is considered accelerating
- If the vehicle was previously considered accelerating, it will not be considered decelerating until it crosses the configurable deceleration threshold
- Similarly, if the vehicle was previously decelerating, it will not be considered accelerating until it crosses the configurable acceleration threshold

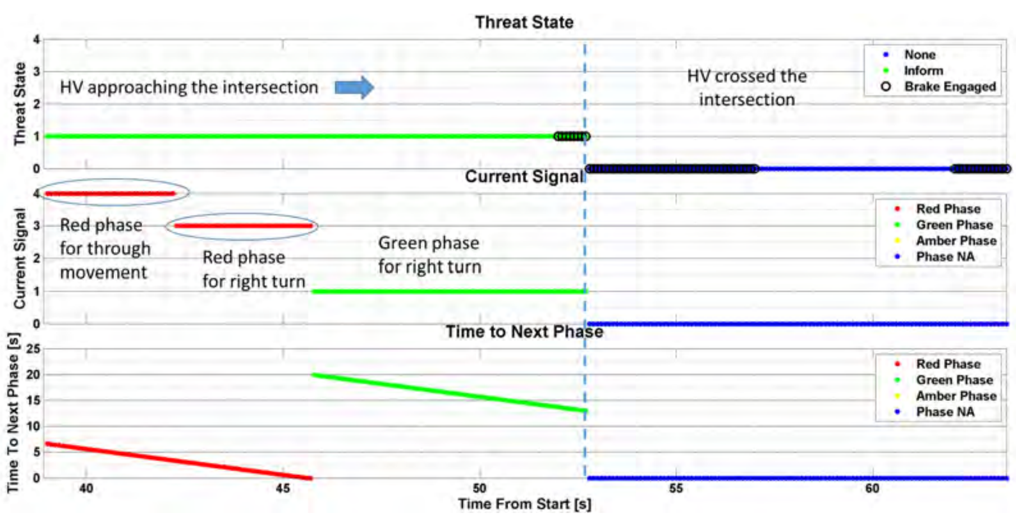
11.1.11.3 Application Validation – Right Turn Signal Indicator Activated

This test is intended to validate appropriate association of the HV's lane with signal phase in the RLVW application. As shown in the top chart of Figure 75, the HV is approaching the intersection on Lane 2. As seen in the bottom chart of Figure 45, initially, no turn signal indicator is activated. During this period, as seen from the middle chart of Figure 75, the application associates the HV's position to the through movement signal phase on Lane 2. When the right turn signal is activated, the application appropriately associates the HV with the right turn signal phase. As a result, when the HV approaches the intersection, the algorithm associates the HV with the right turn signal phase, which is green (as seen in the center chart of Figure 76). Hence the RLVW application appropriately does not generate a Warning, as shown in the top chart of Figure 76.



Source: CAMP – V2I Consortium

Figure 75: Application Validation – Right Turn Signal Indicator Activated

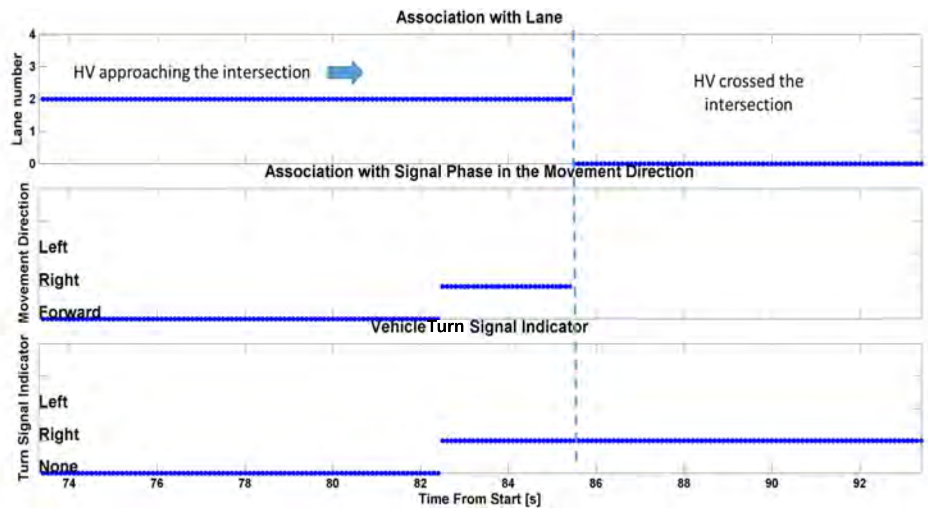


Source: CAMP – V2I Consortium

Figure 76: Warning Status – Right Turn Signal Indicator Activated

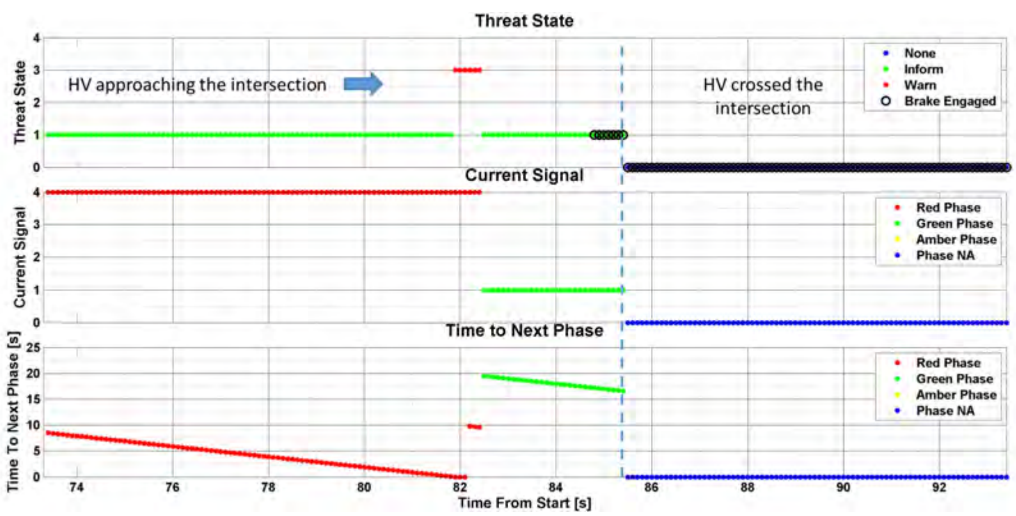
11.1.11.4 Application Validation – Warning Suppression

This test is intended to validate appropriate association of the HV's lane with signal phase in the RLVW application, in response to late right turn signal indicator input by the operator. As shown in the top chart of Figure 77, the HV is approaching the intersection on Lane 2. As seen in the bottom chart of Figure 77, initially no turn signal indicators are activated. As a result, the application appropriately associates the HV's position with through movement on Lane 2 (from the middle chart of Figure 77). The corresponding signal phase for through movement on Lane 2 is shown in the middle chart of Figure 78, which is red. And as seen in the top chart of Figure 78, the application generates a Warning as expected. As soon as the HV operator activates the right turn signal indicator, the application appropriately associates the HV to the right turn signal phase which is green and the Warning is deactivated, as shown in Figure 78.



Source: CAMP – V2I Consortium

Figure 77: Application Validation – Late Activation of Right Turn Signal Indicator

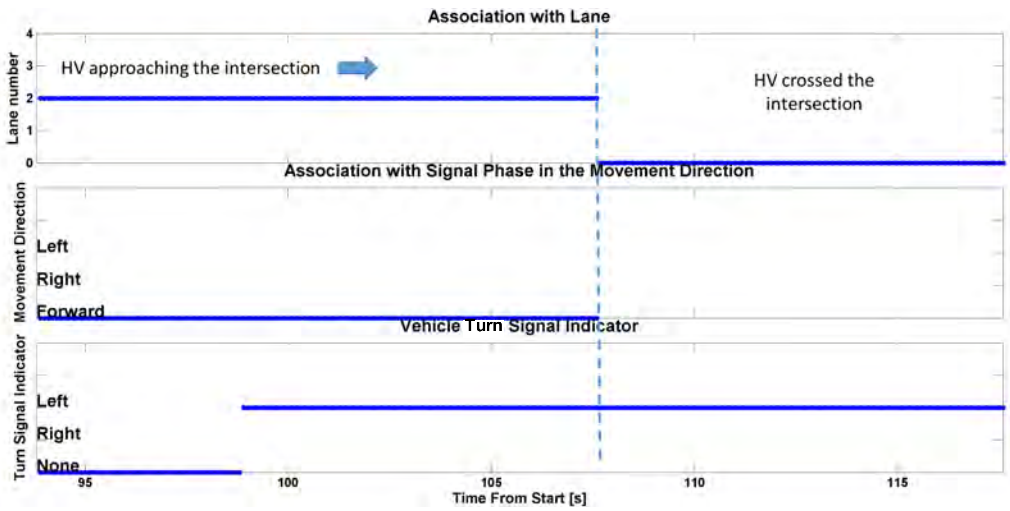


Source: CAMP – V2I Consortium

Figure 78: Warning Status – Late Activation of Right Turn Signal Indicator

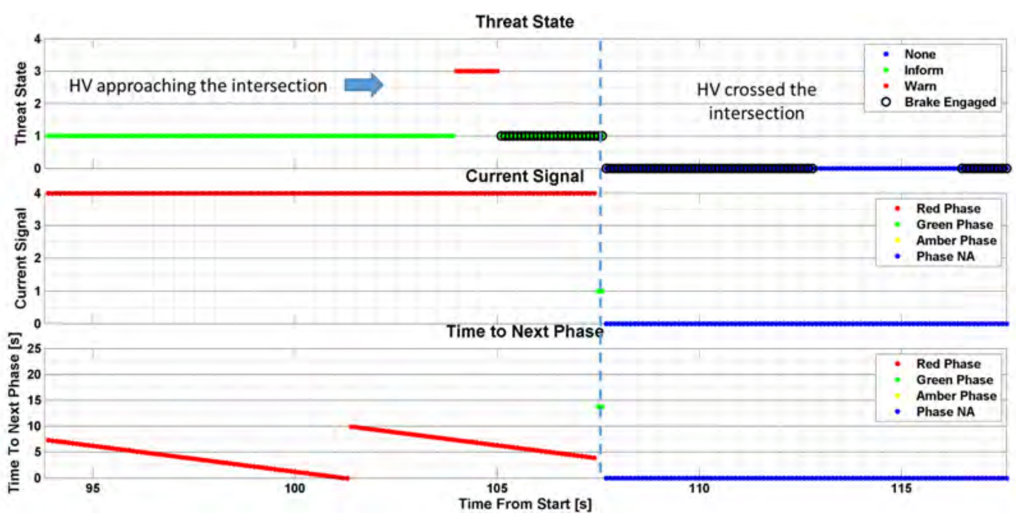
11.1.11.5 Application Validation – Left Turn Signal Indicator Activated

This test is intended to validate appropriate association of the HV's lane with signal phase in the RLVW application in response to left turn signal indicator input by the HV operator. As shown in the top chart of Figure 79, the HV is approaching the intersection on Lane 2. Initially when the turn signal indicator is not activated (as seen in the bottom chart of Figure 79), the application appropriately associates the HV's position to the through movement as seen in the middle chart of Figure 79. The corresponding signal phase for through movement for Lane 2 is shown in the middle chart of Figure 80, which is red. When the left turn signal indicator is activated, the application continues to associate the HV to the through movement signal phase. As a result, when the HV approaches the intersection, the application generates a Warning as shown in the top chart of Figure 80.



Source: CAMP – V2I Consortium

Figure 79: Application Validation – Left Turn Signal Indicator Activated



Source: CAMP – V2I Consortium

Figure 80: Warning Status – Left Turn Signal Indicator Activated

11.2 CSW Test Results and Analysis

All CSW tests were conducted as described in Section 10.3 and APPENDIX E. Test criteria are summarized as follows.

- Inform is generated based on the Approach Speed at a distance corresponding to 8 seconds from the start of the curve.
- In all tests except for Test 2, Warning 1 and Warning 2 are generated as follows:
  - Warning 1 is generated at a distance corresponding to a “comfortable” deceleration rate of 2.4 m/s2
  - Warning 2 is generated at a distance corresponding to an “uncomfortable” or “harsh” deceleration rate of 4.6 m/s2
  - Both Warnings 1 and 2 include an additional distance that corresponds to a 1.8 second driver reaction time and DVI latency
- All distance criteria have an expected range to allow Inform/Warning time (distance) variation of ± 1 second, i.e., (Approach Speed) x (± 1 second)

Table 27 summarizes the results of CSW test cases.

Table 27: CSW Test Summary

Test	Approach Speed (mph)*	Test Objectives	Test Runs	Successful Runs	Remark
1	55 / 40	Base level functionality	16	12	Late map matching generated late Inform
2	35 / 20	Below V_{max} speed, no Warning	14	14	
3	55 / 35	Icy road condition	15	14	Late map matching generated late Inform
4	55 / 40	Reduced visibility	15	14	Late map matching generated late Inform
5	40 / 40	Two radii curve	14	6	• Vehicle slowed down below Vmax speed • Discrete radius calculation, late Warning
6	40 / 40	Two radii curve Icy road condition	15	14	Vehicle slowed down below Vmax, no Warning generated

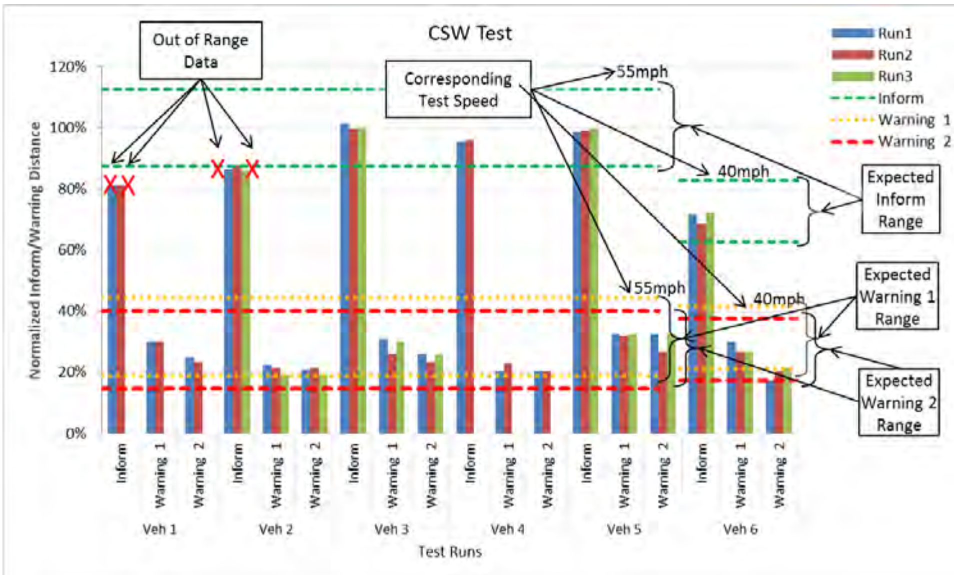
Source: CAMP – V2I Consortium

Figure 81 through Figure 89 show CSW test results. Information provided in these figures is as follows:

- The Y-axis shows Inform and Warning distances from the reference point of the curve normalized to the passenger vehicles’ Inform distance, unless otherwise noted. The Inform is generated first (further from the start of the curve) and is followed by Warning 1 and Warning 2. As such, the Inform bar is taller than the Warning bar, indicating a larger distance measured from the beginning of the curve.
- The X-axis specifies the Inform/Warning runs, number of test runs and number of participating vehicles
- Horizontal dotted lines demonstrate acceptable distance ranges for which Informs and Warnings are provided. For trucks, in some tests, acceptable distance ranges are

different from those for passenger cars due to different test speed and critical speed (speed to Warning).

Out-of-range data are marked by “X” as shown in Figure 81.



Source: CAMP – V2I Consortium

Figure 81: Example of a CSW Test Result

11.2.1 Test 1: Inform and Warning Verification – Single Radius Curve, Dry Road

- Minimum radius of curvature from BIM
- Normal asphalt road
- Road condition dry

Test 1 was conducted at an Approach Speed of 55 mph for passenger vehicles and 40 mph for the truck, for a curvature of 100 m radius, 5˚ superelevation, normal asphalt road and dry road condition. The centripetal V_{max} for the passenger vehicles is 51 mph. For the truck, a V_{max} of 33 mph is based on a stability critical speed (high center of gravity 5 m) to force generation of Warnings at a lower Approach Speed but at different warning distances than for passenger vehicles.

The results from Test 1 are presented in Figure 82. In four out of 16 test runs, recorded Inform distances were slightly lower than the expected range. Further review of the collected test data indicated late map matching on the approach lane resulted in late Inform. This could have resulted due to inaccurate cone placement for the approach lane, resulting in incorrect lane width. This was rectified in subsequent test runs by widening the lane-width parameter in the configuration file by applying padding to the configured lane width for the application.

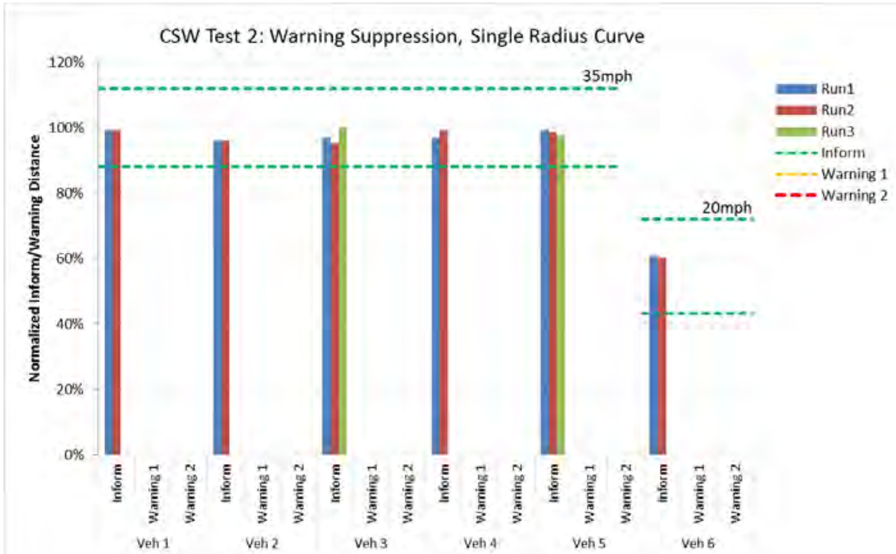
Source: CAMP – V2I Consortium

Figure 82: CSW Test 1 - Single Radius Curve, Dry Road

11.2.2 Test 2: Warning Suppression – Single Radius Curve, Dry Road

- Minimum radius of curvature from BIM
- Normal asphalt road
- Road condition dry

Test 2 was conducted at an Approach Speed of 35 mph for passenger vehicles and 20 mph for the truck, for a curvature of 100 m radius, 5˚ superelevation, normal asphalt road and dry road condition. The V_{max} is 51 mph for the passenger vehicles and 33 mph for the truck. As shown in the graph in Figure 83, appropriate Informs were generated in all test runs. Since the V_{max} is well above the vehicle speed in this test, no Warnings were generated.



Source: CAMP – V2I Consortium

Figure 83: CSW Test 2 – Warning Suppression, Single Radius Curve

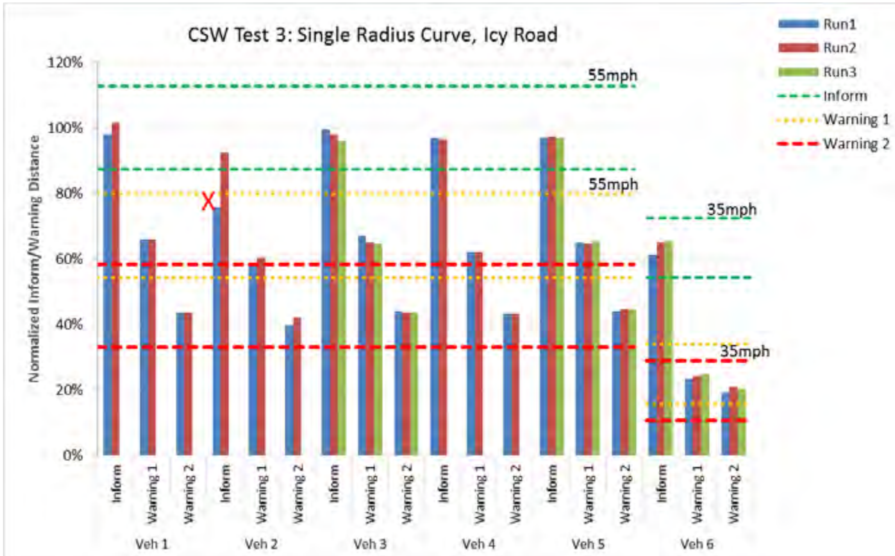
11.2.3 Test 3: Inform and Warning Verification – Single Radius Curve, Icy Road

- Minimum radius of curvature from BIM
- Normal asphalt road
- Road condition icy

Test 3 was conducted at an Approach Speed of 55 mph for passenger vehicles and 35 mph for the truck, for a curvature of 100 m radius, 5˚ superelevation, normal asphalt road and icy road condition with low friction coefficient of 0.15. The V_{max} is 30 mph for the passenger vehicles and 27 mph for the truck.

In comparison to Test 1, in Test 3 the V_{max} is much lower due to the simulated icy road condition. As shown in the graph in Figure 84, Warning 1 and Warning 2 were generated earlier, as expected, for the driver to take appropriate action.

In all Test 3 runs, Inform, Warning 1 and Warning 2 were generated within the expected ranges except in one test run where Inform was generated late due to late map matching on the approach lane. As a result, in 14 test runs out of 15, all messages were generated within expected range as intended in the algorithm as shown in Figure 84.



Source: CAMP – V2I Consortium

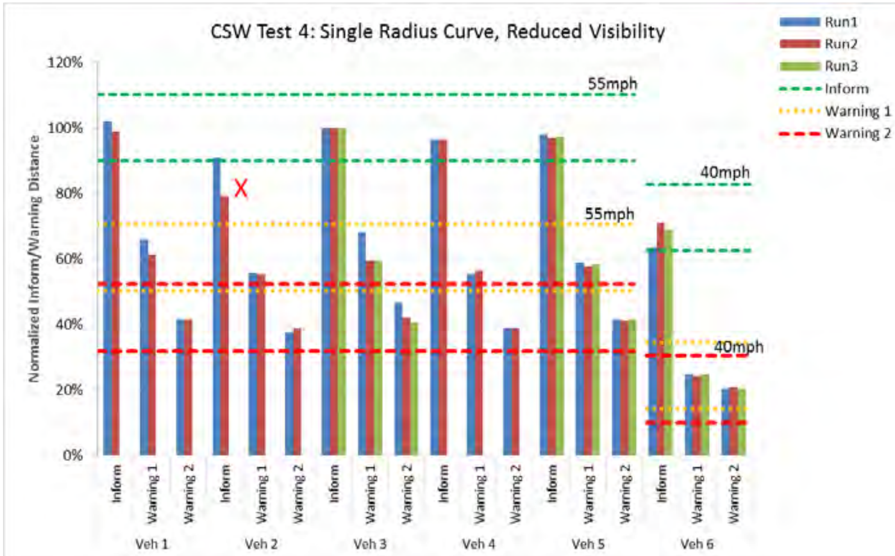
Figure 84: CSW Test 3 – Single Radius Curve, Icy Road

11.2.4 Test 4: Inform and Warning Verification – Single Radius Curve, Reduced Visibility

- Minimum radius of curvature from BIM
- Normal asphalt road
- Reduced visibility

Test 4 was conducted at an Approach Speed of 55 mph for passenger vehicles and 40 mph for the truck, for a curvature of 100 m radius, 5˚ superelevation, normal asphalt road, dry road condition and “low visibility” as received from the BIM. In the algorithm, the V_{max} for low visibility is set to 35 mph which overrides computed V_{max}.

As shown in Figure 85, in all Test 4 runs, Inform, Warning 1 and Warning 2 were generated within the expected ranges except in one test run where Inform was generated late due to late map matching on the approach lane. As a result, in 14 test runs out of 15, all messages were generated within expected range as intended in the algorithm.



Source: CAMP – V2I Consortium

Figure 85: CSW Test 4 – Single Radius Curve, Reduced Visibility

11.2.5 Multiple Radii Curve Tests

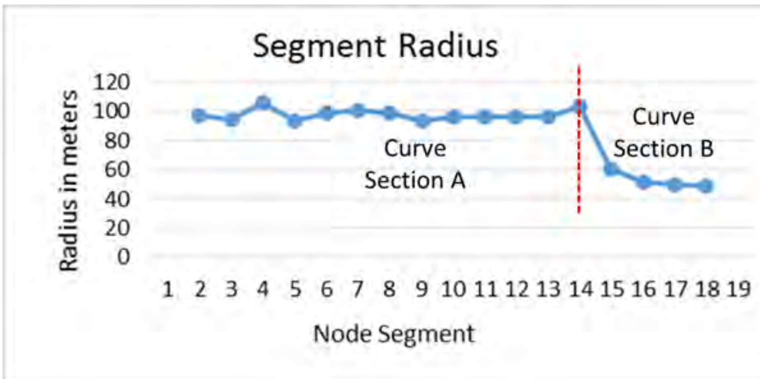
Test 5 and Test 6 utilize a setup and layout comprised of a two radii curve. The curve geometry consists of two distinct radii of a ≈100 m curve followed by a short ≈50 m curve. The 100-meter curve (Curve Section A) contains 14 node map data and the 50 m curve (Curve Section B) contains five node map data. Each node (map data point) is approximately 20 m apart as shown in Figure 138 (see APPENDIX E, Section E.5). The curve geometry is provided in the BIM. Table 28 shows node points and associated computed radii for each node segment, shown graphically in Figure 86. Nodes 1 to 14 represent Curve Section A (100 m) and Nodes 15 to 19 represent Curve Section B (50 m).

Table 28: Node Points and Computed Segment Radii for Tests 5 and 6

Node No.	Latitude	Longitude	Computed Radius (m)
1	42.6097	-84.04754182	–
2	42.60951	-84.04754337	96.86145201
3	42.60932	-84.04759993	94.15982572
4	42.60916	-84.04770579	105.712593
5	42.60902	-84.04784373	93.9771521
6	42.6089	-84.04801169	98.68206954
7	42.60881	-84.04821148	100.8333535
8	42.60875	-84.04844118	98.76762565
9	42.60872	-84.04868192	93.78346268
10	42.60872	-84.04891444	96.17008688
11	42.60877	-84.04916018	96.16484944
12	42.60884	-84.04938149	95.95689636
13	42.60896	-84.04958251	96.58227045

Node No.	Latitude	Longitude	Computed Radius (m)
14	42.60909	-84.04974139	103.6105632
15	42.60925	-84.04986492	60.80363505
16	42.60942	-84.04991183	51.50863411
17	42.60961	-84.04986732	49.40689714
18	42.60975	-84.04973668	48.73363201
19	42.60986	-84.04950749	–

Source: CAMP – V2I Consortium



Source: CAMP – V2I Consortium

Figure 86: Radii of Node Segments for Tests 5 and 6

11.2.5.1 Test 5: Inform and Warning Verification – Multiple Radii Curve, Dry Road

- Radius for curvature not specified in BIM but computed using map data from node points for each node segment
- Curve with multiple radii configuration
- Road surface normal asphalt
- Road surface condition dry

Test 5 was conducted at an Approach Speed of 40 mph for both passenger vehicles and truck, for both curves of 100 m and 50 m radii, 5˚ superelevation, normal asphalt road and dry road condition. The computed V_{max} for each node segment of Curve Section A (Node segments 2 through 14) shown in Table 29 varied between 22.06 m/s (49.36 mph) for Node segment 9 and 23.43 m/s (52.4 mph) for Node segment 4, which is well above the vehicle Approach Speed entering Curve Section A, however, just below the V_{max} for Curve Section B (Node segments 15 through 18) which varied between 15.90 m/s (35.58 mph) for Node segment 17 and 17.76 m/s (39.75 mph) for Node segment 15.

Table 29: Computed Vmax Speed for Test 5

Node No.	Computed Radius (m)	Vmax (m/s) Dry Road	Vmax (mph) Dry Road
1	—	—	—
2	96.86145201	22.42822047	50.17058349
3	94.15982572	22.11322842	49.46596517
4	105.712593	23.43056126	52.4127597
5	93.9771521	22.09176775	49.41795896
6	98.68206954	22.63802073	50.6398941
7	100.8333535	22.88344649	51.1888968
8	98.76762565	22.64783205	50.66184142
9	93.78346268	22.06899015	49.36700683
10	96.17008688	22.3480345	49.99121229
11	96.16484944	22.34742595	49.98985101
12	95.95689636	22.32325012	49.93577112
13	96.58227045	22.39587497	50.09822855
14	103.6105632	23.19644044	51.88904547
15	60.80363505	17.76986387	39.75011928
16	51.50863411	16.3553313	36.58589479
17	49.40689714	16.01817813	35.83170339
18	48.73363201	15.90866434	35.58672761
19	—	—	—

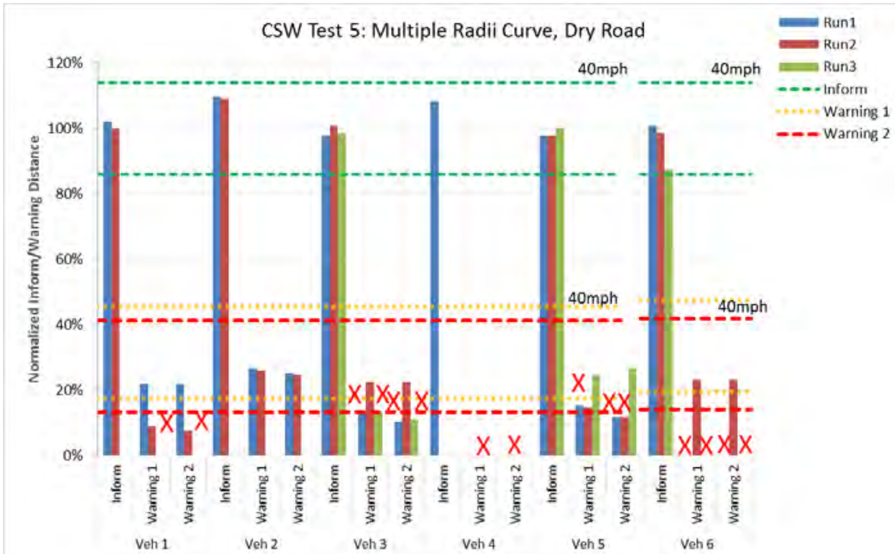
Source: CAMP – V2I Consortium

As depicted in Figure 87, for all test runs, an Inform was generated within the expected range. However, in 3 out of 14 test runs, neither Warning 1 nor Warning 2 were generated for Curve Section B because the vehicle speed dropped below the V_{max}.

In 5 out of 14 test runs conducted, late or no Warnings were generated. Review of test analysis indicated following causes for late Warnings:

- Incorrect placement of Node 15, start of Curve Section B, altered the intended radius of the segment from ≈50 m to 60.80 m. Change in segment radius increased the computed V_{max} for the segment from 36.03 mph to 39.75 mph.
- The vehicle speed of 40 mph being very close to the V_{max} speed of 39.75 mph, the computed distance for Warnings based on deceleration rate of 2.4 m/s^2 for Warning 1 and 4.6 m/s^2 for Warning 2 came to < 1 s between two Warnings for Node 15 (start of Curve Section B)
- When the vehicle speed was lower than 39.75 mph but above 36.6 mph, the warning distance was then calculated based on the next node (Node segment 16) which is 20 m apart and not the intended node segment for Warning
- In case of the truck, the target Approach Speed of 40 mph was difficult to maintain due to abrupt change in curvature radius and short stopping distance after the Curve Section B; consequently, the Approach Speed was well below the Vmax which did not trigger Warnings

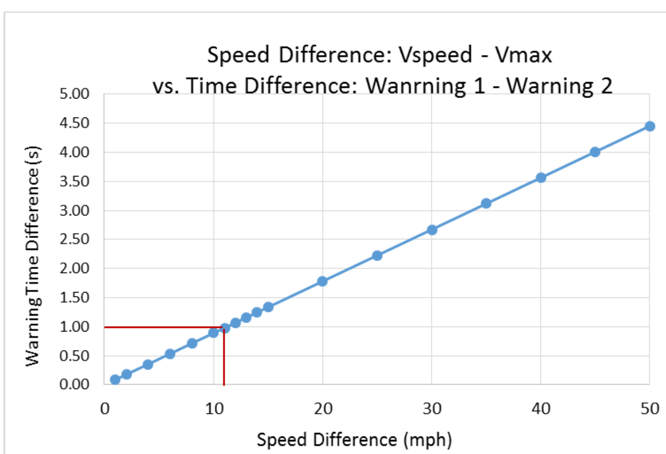
This test result is due to the design of the test, specifically due to the selected vehicle Approach Speeds for Curve Section B. The application algorithm performed as intended.



Source: CAMP – V2I Consortium

Figure 87: CSW Test 5 – Multiple Radii Curve, Dry Road

Further analyses of test results indicate that V_{max} computation for node segments can be enhanced by interpolating between nodes (within a node segment). Additionally, it was observed that to minimize variation in computed radius for node segments, careful placement of the node point is necessary for construction of map data. The Technical Team is further reviewing to address Warnings when the vehicle speed (Vspeed) is not significantly above the V_{max}. For example, when the Vspeed is less than 11 mph above the V_{max}, as shown in the graph in Figure 88, the time difference between two Warnings is less than 1 second. In such conditions, a single Warning (instead of two Warnings as currently implemented) could be generated at a distance of Warning 1 (deceleration rate of 2.4 m/s^2 plus 1.8 s for driver reaction time) from the start of the node segment for driver to take an appropriate action.



Source: CAMP – V2I Consortium

Figure 88: Speed Difference vs. Warning Time Difference

11.2.5.2 Test 6: Inform and Warning Verification – Multiple Radii Curve, Icy Road

- Radius of curvature not specified in BIM but computed from map data for each node segment
- Curve with multiple radii configuration
- Road surface normal asphalt
- Road surface condition icy

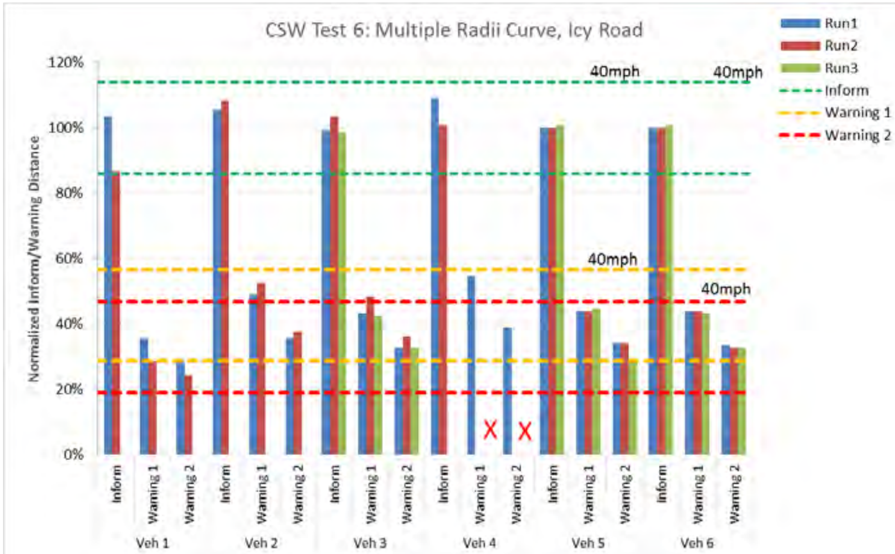
Test 6 was conducted at an Approach Speed of 40 mph for both passenger vehicles and truck, for both curves of 100 m and 50 m radii, 5˚ superelevation, normal asphalt road and icy road conditions. The computed Vmax for each node segment of Curve Section A (Node segments 2 through 14), shown in Table 30 varied between 13.099 m/s (29.30 mph) for Node segment 9 and 13.90 m/s (31.11 mph) for Node segment 4, which is below the vehicle approach speed entering the Curve Section A. Unlike Test 5, in this test, the V_{max} for Curve Section B (Node segments 15 through 18) which varied between 9.44 m/s (21.12 mph) for Node segment 17 and 10.54 m/s (23.59 mph) for Node segment 15 is almost half of the vehicle speed due to low μ.

Table 30: Computed V_{max} Speed for Test 6

Node No.	Computed Radius (m)	Vmax (m/s) Icy Road	Vmax (mph) Icy Road
1	—	—	—
2	96.86145201	13.31277603	29.7798812
3	94.15982572	13.12580539	29.36163911
4	105.712593	13.90773801	31.11077546
5	93.9771521	13.11306693	29.33314394
6	98.68206954	13.43730771	30.058511
7	100.8333535	13.5829857	30.38432403
8	98.76762565	13.44313143	30.07147843
9	93.78346268	13.09954677	29.30290016
10	96.17008688	13.26517984	29.67341139
11	96.16484944	13.26481862	29.67260337
12	95.95689636	13.25046851	29.64050303
13	96.58227045	13.29357663	29.7369333
14	103.6105632	13.76877031	30.79991307
15	60.80363505	10.54770342	23.59457969
16	51.50863411	9.708075713	21.71638289
17	49.40689714	9.50795085	21.26871557
18	48.73363201	9.44294647	21.12330468
19	—	—	—

Source: CAMP – V2I Consortium

In Test 6, Informs for all test runs were generated prior to entering the curve within the expected range. Warning 1 and Warning 2 were also generated within the expected range, except in one test run where Warning 1 and Warning 2 were generated late. This was due to the HV slowing down below the target Approach Speed of 40 mph. Only one out of 15 test runs was outside the expected range as shown in Figure 89.

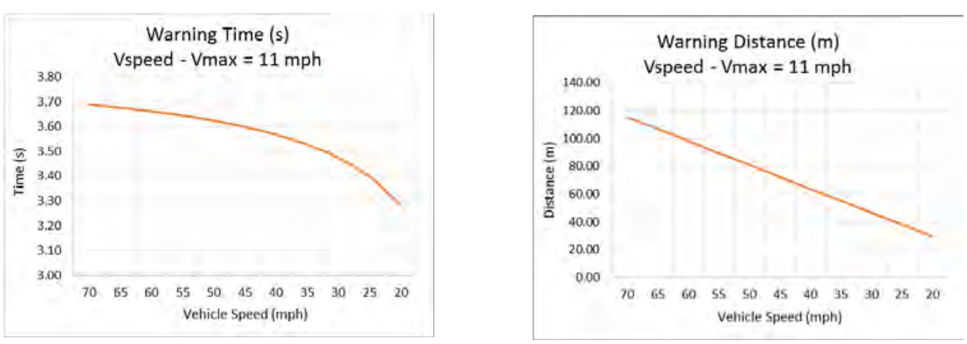


Source: CAMP – V2I Consortium

Figure 89: CSW Test 6 – Multiple Radii Curve, Icy Road

11.2.6 Analysis of Additional CSW Tests at the Test Facility at the University of Michigan

Following the tests conducted at the FTTA test track and detailed test data analysis, the CSW algorithm was further refined for a condition when Vspeed is only slightly (11 mph or less) above the computed speed (V_{max}) for a curvature. Under such conditions, generated warnings (Warning 1 and Warning 2) are less than 1 s apart. The application was further refined to generate only one warning at a distance equivalent to Warning 1 (deceleration rate of 2.4 m/s^2 plus 1.8 s for driver reaction time). Graphs in Figure 90 (a) and (b) show time and distance to approaching node segment for single Warning when the Vspeed is 11 mph above the V_{max} at various vehicle speeds.



(a) (b)

Source: CAMP – V2I Consortium

Figure 90: Time and Distance to Approaching Node Segment for Single Warning

Two passenger vehicles were used to test the modified CSW algorithm at the test facility at the University of Michigan. Three approach speed scenarios (between 15 mph and 45 mph) were tested to validate effectiveness of the modified algorithm implementation of CSW. The test setup had a radius of 35 m, no superelevation, asphalt road and dry road condition. The road surface coefficient of friction μ of 0.5 was used in V_{max} computation. The test layout is shown a satellite image in Figure 91.

Source: Map image Google. Used with permission. Plotted data CAMP – V2I Consortium

Figure 91: CSW Test Layout at the Test Facility at the University of Michigan

11.2.6.1 Inform and Warning Verification – Single Radius Curve

Table 31 shows test scenarios conducted at the test facility at the University of Michigan for CSW and Table 32 shows the summary of conducted tests.

Table 31: Test Runs Conducted CSW Tests at the Test Facility at the University of Michigan

Vehicle Type	Vehicle Speed	Calculated Vmax	Distance to Inform from Reference Point (start of the curve)	Distance to Warning 1 from Reference Point	Distance to Warning 2 from Flag 6 (start of the curve)
Passenger Vehicles	< 24 mph	24 mph	Travel distance in 8 sec ± 1 sec at current vehicle speed	–	–
	24 - 35 mph			Distance (m) = deceleration at 2.4 m/s^2 + (1.8 sec[§] ∗ Vspeed)	–
	> 45 mph			Distance (m) = deceleration at 2.4 m/s2 + (1.8 sec[§] ∗ Vspeed)	Distance (m) = deceleration at 4.6 m/s2 + (1.8 sec[§] ∗ Vspeed)

[§] Indicates driver reaction and display latency time in seconds

Source: CAMP – V2I Consortium

Table 32: Summary of CSW Tests Conducted at the Test Facility at the University of Michigan

Approach Speed (mph)*	Test Objective	Test Runs	Successful Runs	Remarks
15 – 45 (various approach speed profiles)	Evaluate warnings generated when the vehicle speed is close to computed V_{max}	12	12	• Radius of curvature computed from map data for each node segment • Curve with single radius configuration • Road surface asphalt • Road surface condition dry

Source: CAMP – V2I Consortium

Though the physical radius of the curve was 35 m, the radii calculated by each node segment varied between 28 m and 43 m, thereby resulting in a variation of the V_{max} between 21 mph and 26 mph as shown in Table 33.

Test vehicle Approach Speed was varied between 15 mph and 45 mph. Two passenger vehicles were tested on the curves of 35 m radius, no superelevation, asphalt road and dry road conditions. The computed V_{max} is 10.6 m/s (24 mph) for the given radius. But actual radii calculated for each node segment varies between 28 m and 43 m, resulting in variation in the V_{max} between 21 mph and 26 mph as shown in Table 33.

Table 33: Computed V_{max} Speed for CSW Tests at the Test Facility at the University of Michigan

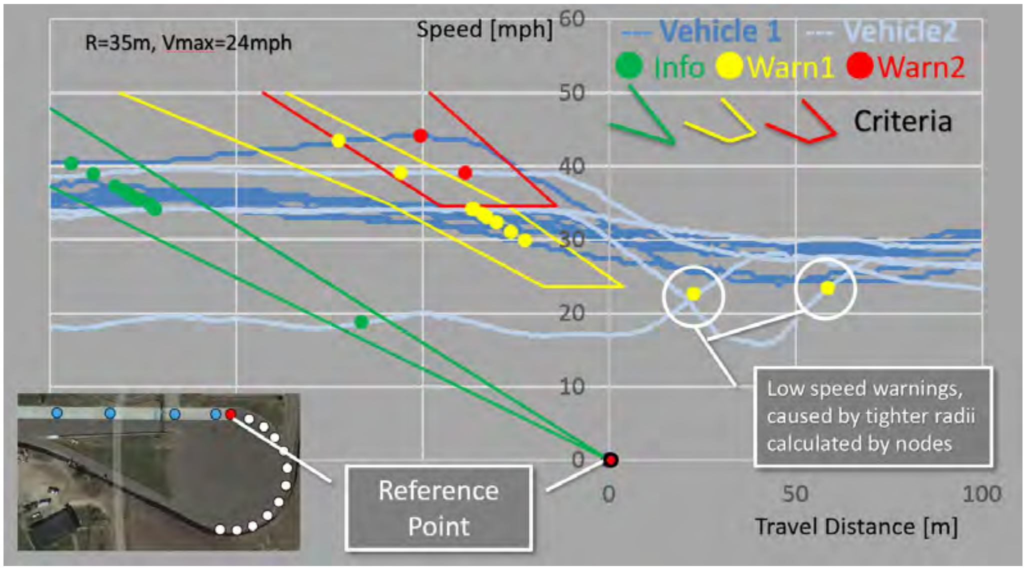
Node No.	Computed Radius (m)	V_{max} (m/s) Dry Road*	V_{max} (mph) Dry Road*
1	-	-	-
2	40.00972	11.28853	25.25713
3	35.16992	10.58377	23.68028
4	37.95849	10.99535	24.60116
5	28.31416	9.496347	21.24727
6	39.20962	11.17509	25.00331
7	33.19573	10.28243	23.00606
8	37.02014	10.8586	24.29519
9	43.49523	11.76997	26.33431
10	30.3832	9.8372	22.00989
11	35.73972	10.66916	23.87134

* - Coefficient of friction μ of 0.5 applied for V_{max} computation

Source: CAMP – V2I Consortium

11.2.6.2 Test Result Analysis

A composite graph of all test runs is shown in Figure 92. The graph consists of Inform, Warning 1 and Warning 2 for each test run indicated by green, yellow and red dots and lines, respectively. Each color-bounded region denotes the criteria (speed-distance) for meeting Inform / Warning(s) at various Approach Speeds.



Source: CAMP – V2I Consortium

Figure 92: Composite Graph of 12 CSW Test Runs

The dark blue lines indicate six test runs from Vehicle 1, and the light blue lines indicate test runs from Vehicle 2. Vehicle Approach Speeds vary from 15 mph to 45 mph, as indicated by the dark and light blue lines before and after the reference point, indicated by a red dot with black outline. For the analysis, the computed V_{max} of 24 mph is used, based on a fixed radius of curvature of 35 m. However, the curve is mapped with multiple nodes and the radii of the curve is computed for each node segment. Due to the variation in placement of nodes on the curve for mapping, the computed radii for node segments varies between 28 m to 43 m and the associated V_{max} varies between 21 mph to 26 mph.

Out of the 12 test runs, a Warning was issued when the vehicle speed was below the V_{max} of 24 mph. In these cases, the computed radii of node segments are below 35 m, causing lower V_{max} as indicated by two the yellow dots outside the yellow-bounded area in Figure 92.

In the case of two test runs, map matching was discontinued in the middle of the curve as shown in Figure 93. This was caused due to the test vehicles moving out of the mapped lane, resulting in no map matching.

Source: Google. Used with permission.

Figure 93: Discontinuation of Warning

Consistent placement of nodes in creating a map for a curve is one of the critical elements that cause variations in the iterative computation of the radii. Ideally, the nodes should be placed exactly on the originally designed geometric drawing of the roadway to minimize variation in radii. In the future, one could use GPS coordinates from actual vehicles driven on a curve to improve mapping accuracy.

11.3 RSZW/LC Test Results and Analysis

All RSZW/LC tests were conducted as described in Section 5. Test criteria are summarized as follows:

- Inform is generated based on the Approach Speed at a distance corresponding to 10 seconds from the start of the work zone and the Warning at a distance corresponding to 5 seconds
- All distance criteria have an expected range to allow Inform and Warning time (distance) variation of ± 1 second, i.e., (Approach Speed) x (± 1 second)

Table 34 summarizes the results of RSZW/LC test cases.

Table 34: RSZW/LC Test Summary

Test	Test Objectives	Test Runs	Successful Runs	Remark
1 and 6 2 and 7	**Reduced speed** • Workers not present • Workers present	36	30	Six runs were conducted due to temporary test equipment issue in one test vehicle
3 and 8 4 and 9	**Lane closures** • One lane closure • Two lane closures o Warning suppression	36	36	
5 and 10	**Two lane closures and reduced speed** • Lane closures o Warning suppression • Reduced speed o Workers present	18	17	Missed one run due to temporary test equipment issue in a test vehicle

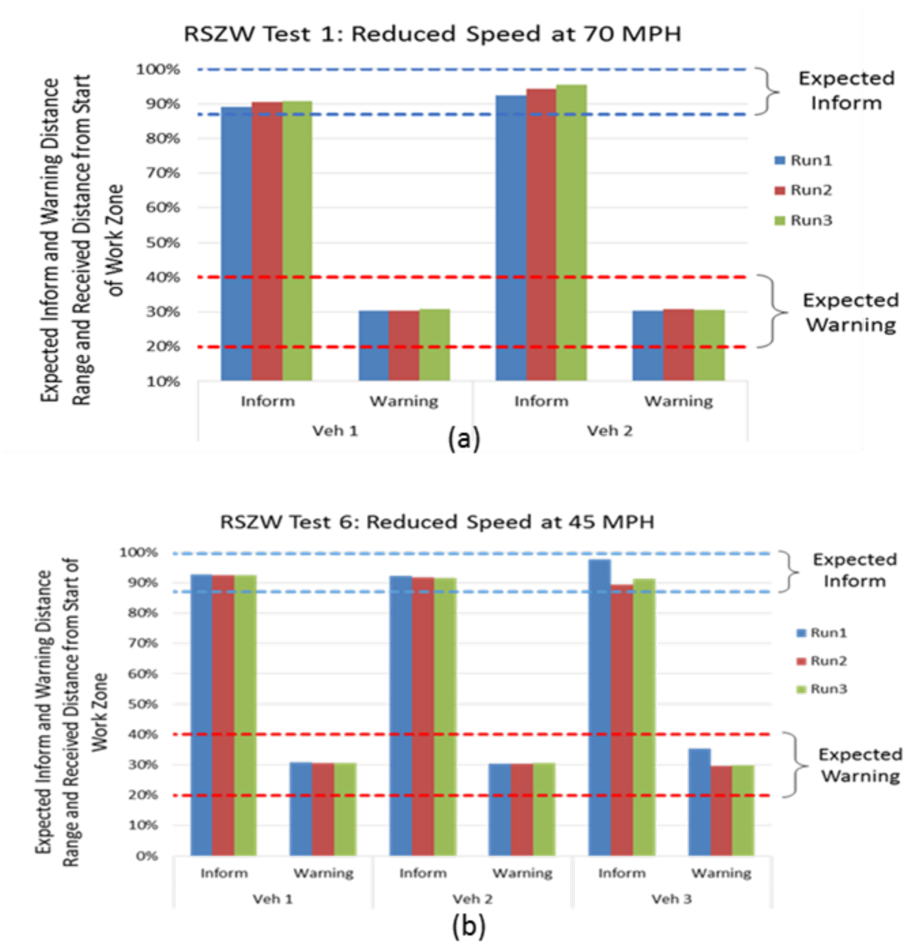
Source: CAMP – V2I Consortium

The following subsection presents tests results and analysis for RSZW/LC application objective testing. Information provided in Figure 94 through Figure 98 is as follows:

- The Y-axis represents Inform and Warning distances from the beginning of the work zone (reference point) normalized to the furthermost approach distance. Inform is generated first (at a certain Inform duration prior to the start of the work zone) followed by Warning. Thus, the Inform bar is taller than the Warning bar, indicating occurrence of Inform at a longer distance from the beginning of the work zone compared to Warning. In case of two lane closures, the y-axis represents the normalized distance from the start of the lane closures to the farthest approach distance where Inform and Warning are received.
- The X-axis represents number of test runs, lane closures and number of participating vehicles in a test
- Horizontal dashed lines represent expected distance range from start of work zone for Inform and Warnings to be generated by the application

11.3.1 Tests 1 and 6: Reduced Speed

This is a simple RSZW test conducted at two different Approach Speeds. The HV approached the work zone at around 70 mph for Test 1 and 45 mph for Test 6. For Test 1, two vehicles performed the test while for Test 6, three vehicles performed the test. In both test cases, all HVs received Inform and Warning messages within the expected zones. Test results are shown in Figure 94 (a) and (b).

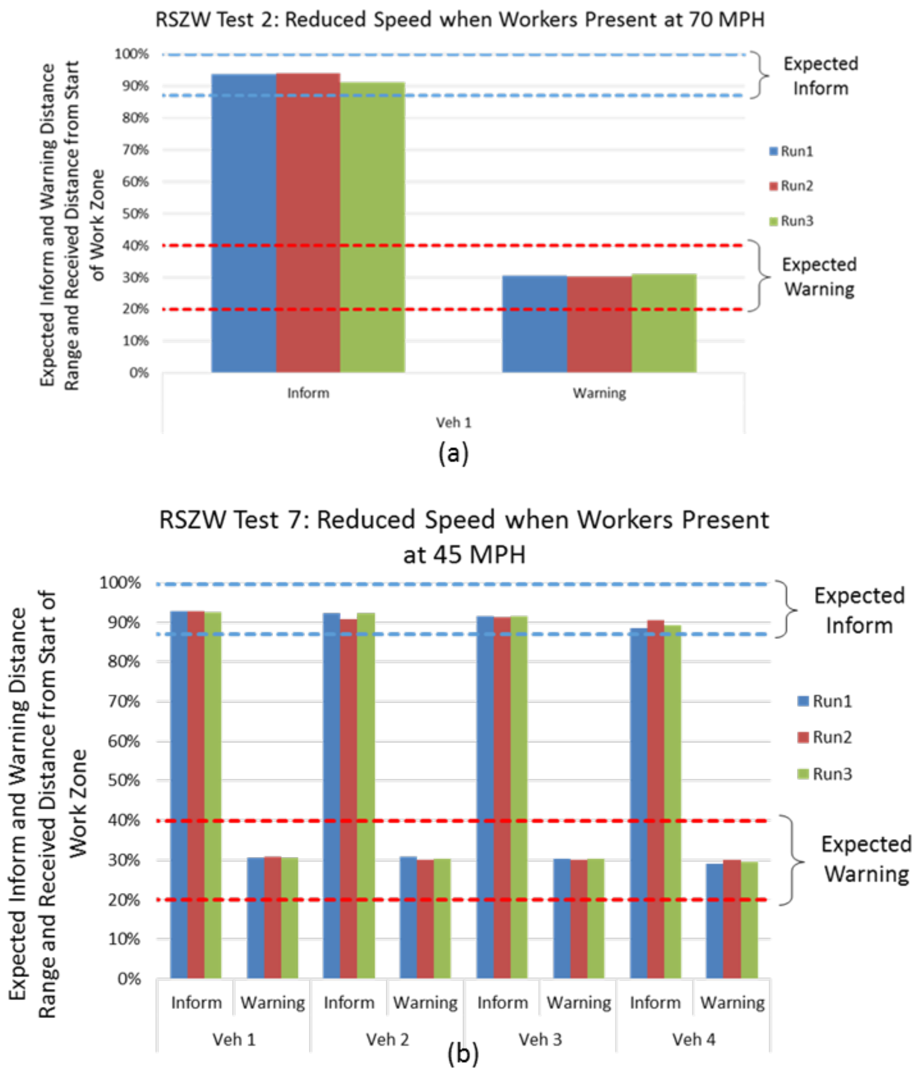


Source: CAMP – V2I Consortium

Figure 94: RSZW/LC Test 1 and Test 6 – Reduced Speed at 70 mph and 45 mph

11.3.2 Tests 2 and 7: Reduced Speed when Workers Present

This is a reduced speed test in work zone when workers are present. The test was conducted at two different Approach Speeds. The HVs approached the work zone at around 70 mph for Test 2 and 45 mph for Test 7. For Test 2, one vehicle performed the test while for Test 7, four vehicles performed the test. In both test cases, all HVs received Inform and Warning messages within the expected zones. Test results are shown in Figure 95 (a) and (b).

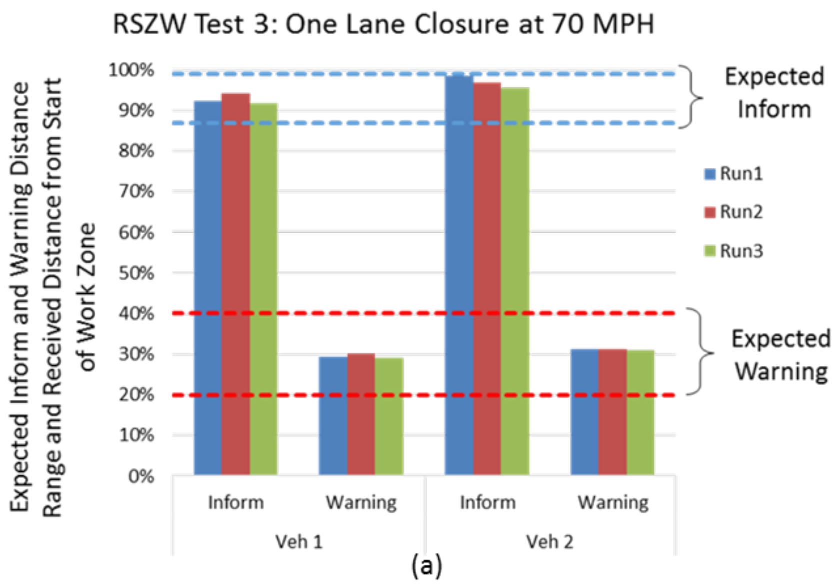


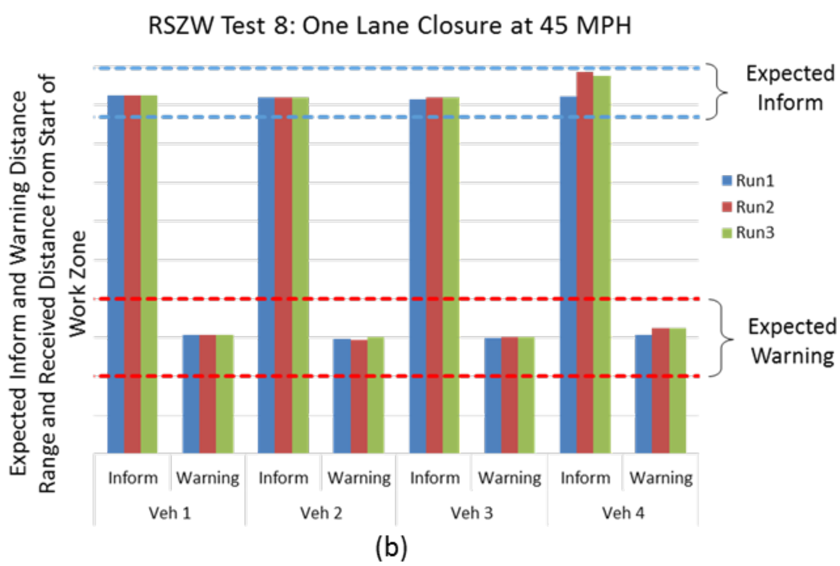
Source: CAMP – V2I Consortium

Figure 95: RSZW/LC Test 2 and Test 7 – Reduced Speed when Workers Present at 70 mph and 45 mph

11.3.3 Tests 3 and 8: One Lane Closure

This is a one lane closure test in work zone. The test was conducted at two different Approach Speeds of 70 mph for Test 3 and 45 mph for Test 8. For Test 3, two vehicles performed the test while for Test 8, three vehicles performed the test. In both test cases, all HVs received Inform and Warning messages for lane change within the expected zones. Test results are shown in Figure 96 (a) and (b).



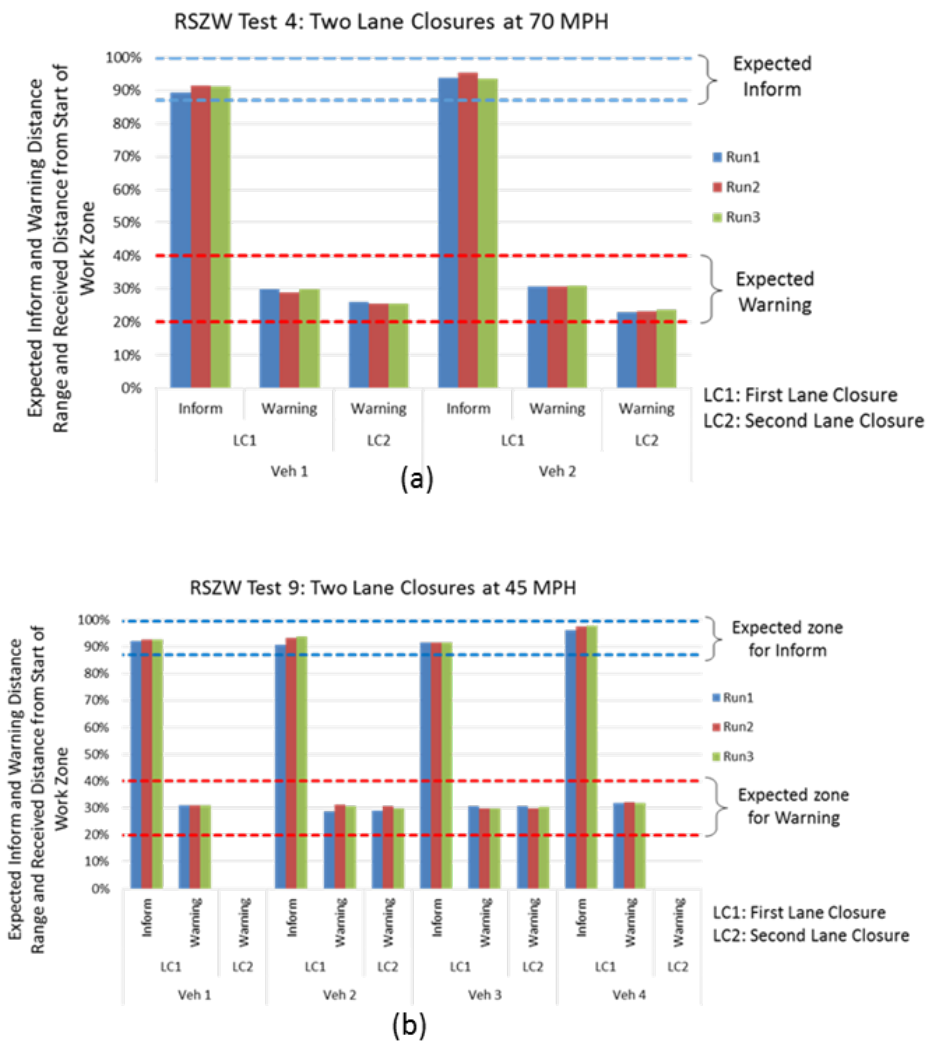


Source: CAMP – V2I Consortium

Figure 96: RSZW/LC Test 3 and Test 8 – One Lane Closure at 70 mph and 45 mph

11.3.4 Tests 4 and 9: Two Lane Closures

This is a two-lane closure test in a work zone. The test was conducted at two different Approach Speeds of 70 mph for Test 4 and 45 mph for Test 9. In both test cases, HVs received one Inform message for the lane closure ahead and Warning messages for each closed lane. For Test 4, two vehicles performed the test while for Test 9, four vehicles performed the test. The data for two vehicles (Vehicles 1 and 4) do not appear in the graph due to a procedural error while logging data. In both test cases, all HVs received Inform (common for both lane closures) and Warning messages for lane change within the expected zones. Test results are shown in Figure 97 (a) and (b).



Source: CAMP – V2I Consortium

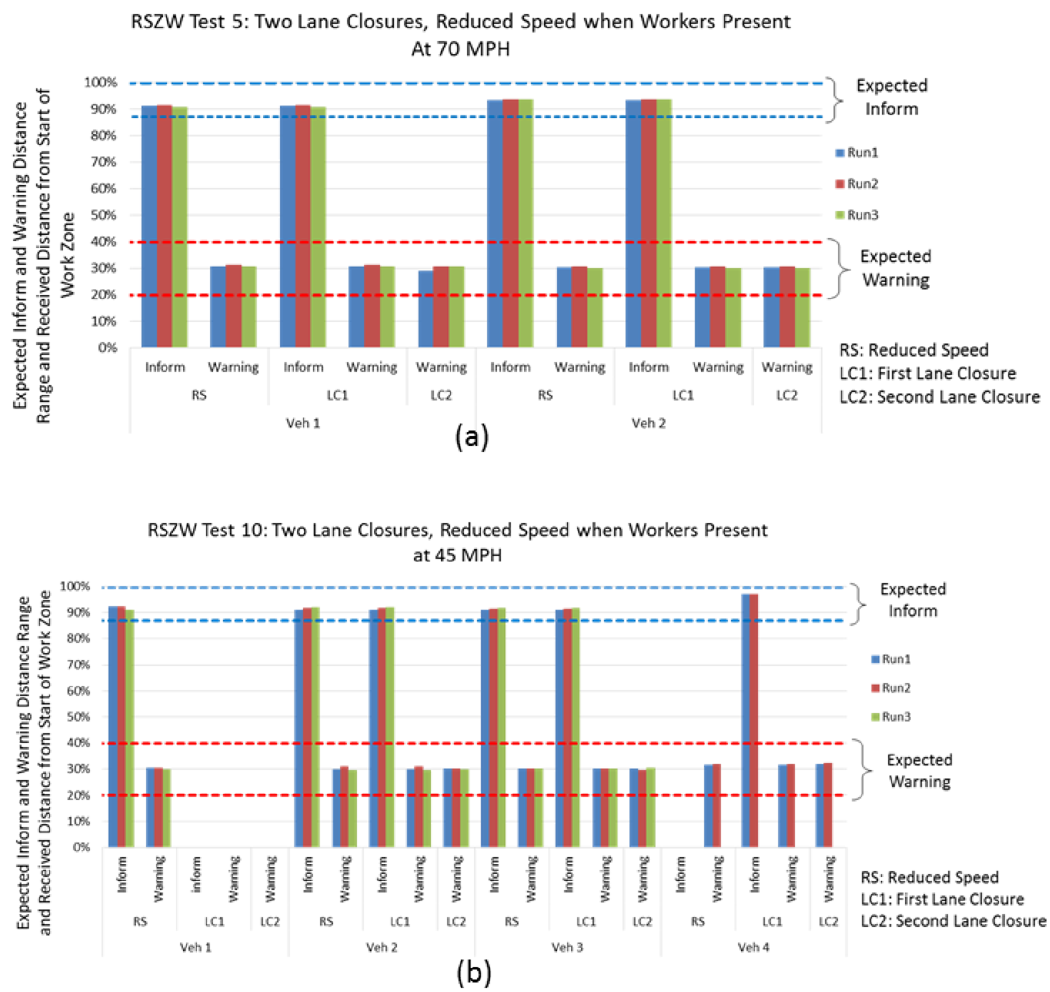
Figure 97: RSZW/LC Test 4 and Test 9 – Two Lane Closures at 70 mph and 45 mph

11.3.5 Tests 5 and 10: Two Lane Closures and Reduced Speed

This test combines two lane closures with reduced speed when workers are present in work zone for proper Inform and Warnings for two lane closures and reduced speed. The test was conducted at two different Approach Speeds of 70 mph for Test 5 and 45 mph for Test 10. In both test cases, HVs received the following:

- Informs are generated prior to entering the work zone for approaching lane closure and for reduced speed in work zone
- Warnings for Lane Closure 1 and 2 are also generated
- Warning for reduced speed is generated for workers present in work zone

For Test 5, two vehicles performed the test while for Test 10, four vehicles performed the test. The test data for Vehicles 1 and 4 in the graph are not available in the test log. In both test cases, all HVs received Inform and Warning messages for lane change and reduced speed within the expected zones. Test results are shown in Figure 98 (a) and (b).



Source: CAMP – V2I Consortium

Figure 98: RSZW/LC Test 5 and Test 10 – Two Lane Closures, Reduced Speed when Workers Present at 70 mph and 45 mph

11.4 Observations and Lessons Learned

During the course of development of safety applications in this project, several observations were made. Lessons learned are described here.

11.4.1 Red Light Violation Warning

During the first OTP test scenario conducted in February at Fowlerville test facility, the RLVW application exhibited unexpected behavior. By repeating the test and closely watching the data shown on the eGUI, the experimenter noticed that the signal timing value broadcast in the SPaT message was in hours and not in seconds as programmed in the signal controller. The signal timing is expressed in one tenth of a second of the current hour or the next hour of Coordinated Universal Time

(UTC). The timing information is generated by the RSU from the input from the signal controller to convey details about the timing of a phase within a movement and the time stamp (time mark) at which the related phase will change to the next state. Further investigation revealed that the RSU's internal clock used to generate the signal timing value in the message was off by several hours. It was further discovered that the RSU clock was not synchronized to the UTC time and the RSU's internal clock had drifted significantly.

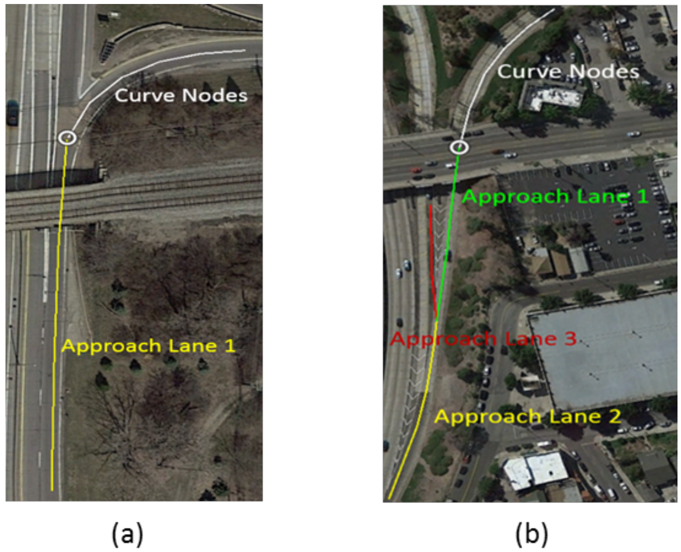
It is very important that both the RSU and the On-Board Unit (OBU) internal clocks are synchronized to the UTC time for correct operation of an application. Unexpected application behavior will also result when the internal clock of an OBU is not synchronized with UTC.

The following time accuracies are recommended:

- The RSU system clock shall be accurate to within 10 ms of the reference time
- All absolute times in the SPaT message shall be determined based on the RSU system clock
- The time difference between minEndTime (in the UTC reference system) and the earliest possible physical phase change shall be no larger than 100 ms
- The time difference between maxEndTime (in the UTC reference system) and the earliest possible physical phase change shall be no larger than 100 ms
- The data elements MinuteOfTheYear and DSecond shall be present in each transmitted message and accurate within 100 ms of UTC time

11.4.2 Curve Speed Warning

In the real-world driving, quite often, an approach lane may present possibilities of either to go straight or to go on a curve leading to a freeway. Though such a scenario was not tested at the test facility, for single approach lane scenario, classifying the approach accurately would prevent false Inform / Warnings if the vehicle is going to travel straight as shown in Figure 99 (a). The application should trigger only if the vehicle operator intends to go on the curve. Knowledge of the driving route or turn signal indicator could be used to ascertain the intent of the vehicle operator to generate appropriate Inform and/or Warnings. Figure 99 (a) and (b) depicts such scenarios where the optional data element "approachClassification" allows the classification of approach lanes based on the certainty with which they lead to the curve. The curve that is being described is relevant only for approaching vehicles that will turn right. However, the same lane is also being used by vehicles that will continue to go straight. In such a situation, the single approach lane shall be encoded with lane classification information.



Source: Google. Used with permission.

Figure 99: Example Approach Scenarios for CSW

11.4.3 Mapping Requirements for Reduced Speed Zone / Work Zone / Lane Closure Warning

During the OTP testing of the application, an observer (technical team member) riding in the test vehicle noticed “geometry retry” when the test vehicle was transitioning from approach lane geometry to work zone lane geometry. Examination of the logged data indicated the following conditions that contributed to temporary dropout in map matching:

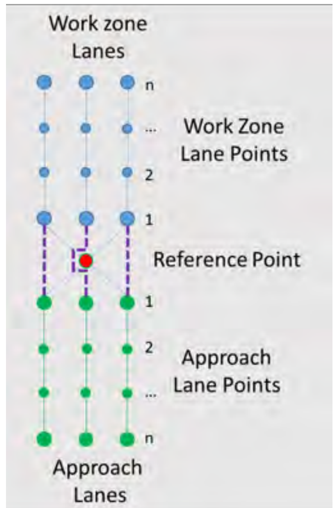
- The reference point was used as a data point for map matching from the end of the approach lane to start of the work zone lane

The large distance (purple dashed line in Figure 100) between the first data point of an approach lane and the first data point of corresponding work zone lane

In addition to the geometry of the physical lane, setting the reference point, classifying the approach and work zone lanes are critical for the map matching that may eventually impact the performance of the safety application.

11.4.3.1 Lane Layout

The DSRC message format for the application supports multiple approach lanes leading to the event and (depending on the use case) multiple geometry (work zone) lanes. The graphic in Figure 100 shows an example of an application that supports three lanes. The event begins at the Reference Point and three approach lanes describe trajectories into the work zone.



Source: CAMP – V2I Consortium

Figure 100: Example of RSZW/LC Lane Mapping Scenario

The following general rules apply to the layout of those lanes:

1. Map points (node list) for lanes are always defined as moving away from the reference point. Therefore, vehicles are traversing an approach lane against the definition and the geometry (work zone) lanes with the definition
2. The potential connection between the reference point and the first node point of the approach and the geometry point shall not be used for map matching, as shown in Figure 100 as purple dashed lines
3. All approach lanes that logically connect to one or more geometry (work zone) lanes shall specify this connection through the “connectsTo” data frame as defined by SAE J2735 standards

A "connection" is defined as an approach lane physically leading to a geometry (work zone) lane without requiring a vehicle to perform a lane change maneuver.

12 Automatic Intersection Map Generation

CV technology has gained significant attention in the U.S. due to its potential to improve safety and mobility performance of the transportation system. One crucial element of many CV applications is an accurate representation of road segments, i.e., location maps). At signalized intersections, such location maps, or Geometric Intersection Description (GID) maps, are conveyed in SAE J2735 MAP messages for broadcasting by RSUs. However, if GID maps are manually surveyed, creation and maintenance of MAP messages could be costly and challenging for public agencies, especially for a large-scale deployment.

An approach for automatically generating intersection maps using BSMs received by RSUs was developed during the project. The work was conducted by the University of Michigan Transportation Research Institute in cooperation with the V2I SA TMT. The proposed approach was applied to five intersections selected from the Safety Pilot Model Deployment Project database to estimate intersection maps. The estimated maps were then compared with reference maps obtained from LIDAR surveys to evaluate the effectiveness and accuracy of the proposed approach. The developed methodology showed potential for use as an automated map generation tools in the future. A detailed report of this effort has been prepared and is available as a separate document [2].

13 Feasibility Assessment for Actuated Traffic Signal Control

The U.S. Department of Transportation (USDOT) is interested in advancing the deployment of DSRC in the vehicle fleet as well as supporting the development of applications based on V2V and V2I communication. In December 2016, the National Highway Traffic Safety Administration (NHTSA) issued a Notice of Proposed Rulemaking (NPRM) to create Federal Motor Vehicle Safety Standard (FMVSS) 150 to require V2V safety communications in all new light trucks and passenger vehicles. [21] Additionally, in January 2017, the FHWA released V2I guidance that is intended "to improve safety and mobility by accelerating the deployment of V2I communication systems." [22] The deployment of vehicle communications in the fleet can lead to enhanced safety in transportation, increased mobility, and reduced environmental impact of transportation. Furthermore, there is potential to provide substantial benefits for the autonomous vehicles of the future. For the purposes of this report, this specific V2V and V2I communications will be referred to as CV technology.

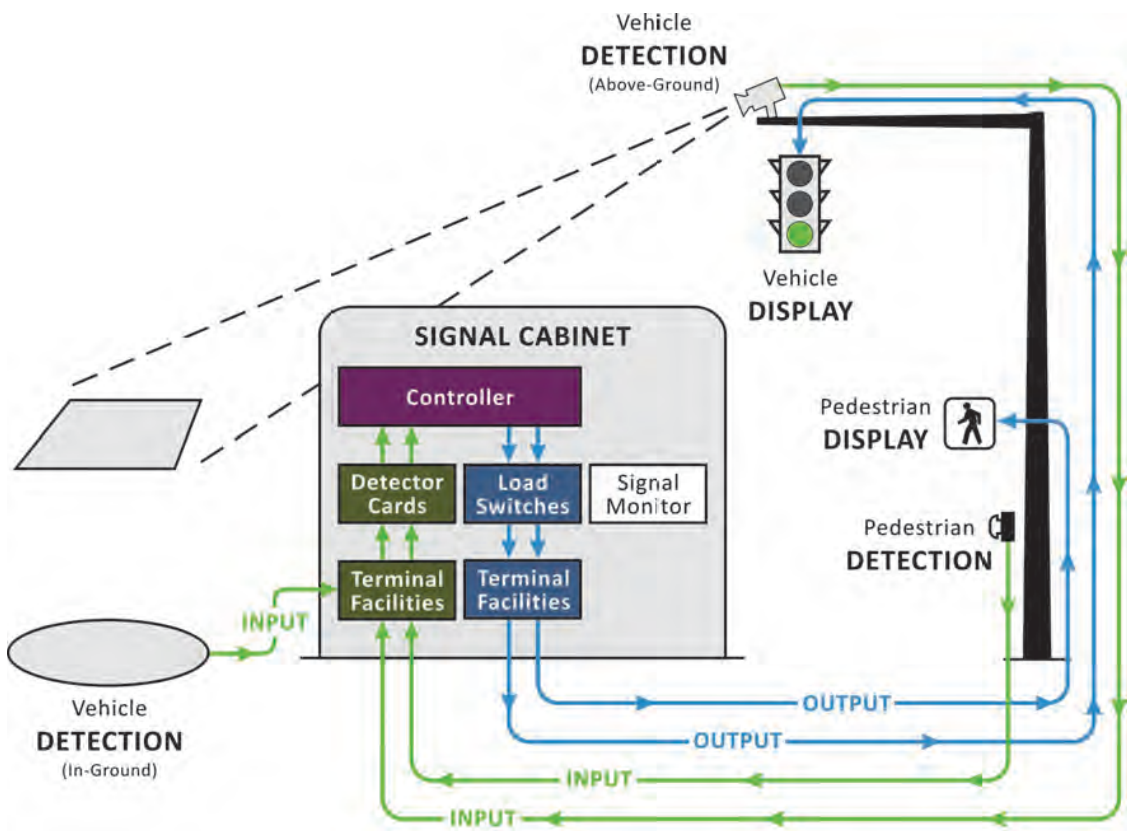
One such application to improve intersection safety is the RLVW. This application enables vehicles equipped with CV technology to receive information about the signal timing and the geometry of the intersection through wireless messages broadcasted from the infrastructure when approaching a signalized intersection similarly equipped with this CV technology. The data elements forming these wireless, or OTA, messages are specified in the SAE J2735 standard. Conventional signal systems use pre–programmed, daily signal timing schedules for controlling signal phases. Adaptive signal control technology adjusts the signal timings to accommodate changing traffic patterns and ease traffic congestion in a manner that is more dynamic than the methods used by a conventional signal controller.

This chapter presents the results of a study to assess the feasibility of using the existing RLVW application developed earlier in the V2I-SA Project with actuated traffic signals. The Texas Transportation Institute (TTI) assisted in this effort. The task began with instructional meetings conducted by TTI to provide the V2I-SA TMT with a working-knowledge of actuated traffic signal control, as well as a basic understanding of the technical characteristics and the range of operational features available across the various traffic signal controller suppliers and product lines. TTI then assessed the functionality of the current RLVW application under the various traffic signal operating modes. As part of the assessment, TTI provided preliminary recommendations for implementing new features in the RLVW application associated with actuated signal control. The scope of this assessment did not include implementing and testing any of the suggested application modifications. The following sections provide a summary of knowledge transferred to the TMT and also documents the result of TTI's assessment.

13.1 Basic Operation of a Traffic Signal

The MUTCD [8], the standard by which transportation agencies design, install, and operate traffic control devices, states that the purpose of a traffic signal is to safety and efficiently "assign the right-of-way to the various traffic movements" at an intersection. Achieving safe and efficient traffic signal operation requires considerable engineering practice and judgement. This engineering practice is influenced by local community goals and objectives, in addition to local practice. The following provides a brief introduction into traffic signal operation and the potential impacts of these operations on the CAMP RLVW application.

Figure 101 shows the basic components associated with every traffic signal: a traffic signal controller, a traffic signal cabinet, displays (or signal indications) used to control the movement of traffic at the intersection, and a detection system. User needs for movement are determined through the detection system. The detectors alert the traffic signal controller of the presence (or pending arrival) of different types of user classes. Different types of detection systems are used for different types of users. The controller then uses these detector inputs to determine which signal indications to display to the users at the intersection. The durations of signal indications are based on signal timing parameters as defined by the responsible operating agency within a specific jurisdiction. As the number of users simultaneously approaching the intersection from the various approaches (e.g., directions) increases, the determination of which intersection approach to service also increases in complexity. In this situation, the controller determines its outputs based on timing parameters that reflect the priorities and preferences of local agencies, constrained by state and federal standards and engineering practice. As a result, the manner in which the controller assigns time to users is highly dependent upon the detection and signal timing parameters (controller settings) programmed into the controller by the operating jurisdiction.



Source: Traffic Signal Timing Manual, 2nd Edition [23]

Figure 101: Basic Components of a Traffic Signal

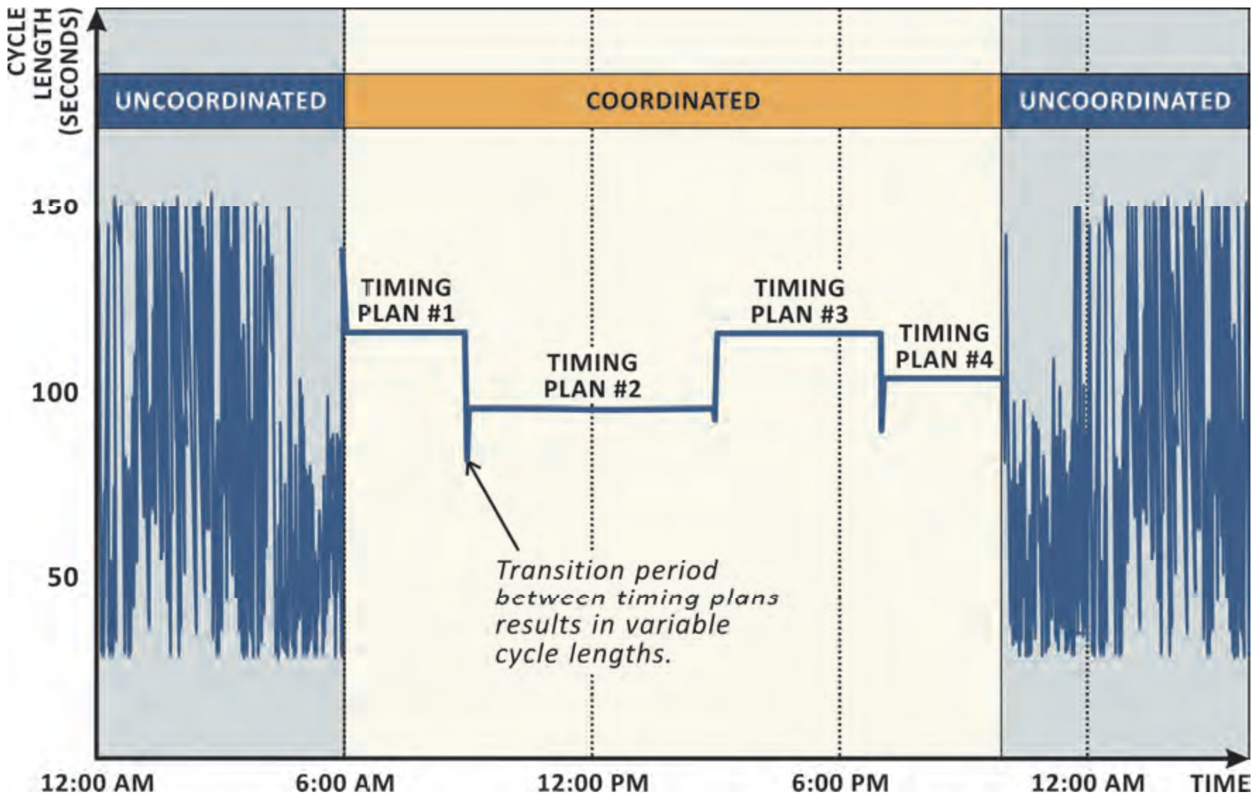
A traffic signal can be programmed a number of different ways: 1) to respond to the demands at the local intersection, 2) to operate in relationship with other intersections or 3) both. When designed to respond to demands at local intersections, the controller can operate in three modes: fully actuated, semi-actuated, and fixed time (or pre-timed). Figure 102 highlights the differences between these operating modes. In fully actuated mode, a traffic signal controller uses information from detectors to adjust the signal timing to respond to current user demands for service. A traffic signal that only utilizes detectors on certain approaches (generally those associated with minor movements at the intersection) is operating in a semi-actuated mode, only adapting its operation based upon partial demand information. A controller that does not respond to any detection inputs operates in a fixed (or pre-timed) mode. Pre-timed signal systems are generally used in special cases (e.g., grid networks in Central Business Districts). Pre-timed systems are generally less costly to build because they do not require a detection system, and their timings are based upon historical traffic demands.

Source: Signal Timing Manual, 2nd Edition [23]

Figure 102: Typical Operating Modes for Traffic Signals

Traffic signals can also operate in coordination with other intersections on an approach. Traditional traffic signal systems utilizing coordination to minimize the number of stops for through traffic impose a common cycle length to maintain a consistent relationship between adjacent traffic signals. This coordination essentially constrains the local traffic signal controller to a timing plan established to specifically achieve the operational objective of corridor progression (resulting in fewer stops along the corridor). For example, Figure 103 illustrates how a traffic signal can change its operation at an intersection relative to the time-of-day.

Some intersections can operate both alone or as part of a system during different times of day. Uncoordinated signal timing allows the intersection to run independently (or “free”) of any other intersection, while coordinated timing s allow several signals to operate as a system. One common misperception is that detection cannot be utilized to influence the coordinated phases if an intersection is coordinated. Modern controllers can actuate a portion of the coordinated phases, providing additional flexibility.



Source: Signal Timing Manual, 2nd Edition [23]

Figure 103: Example of Daily Fluctuation in Traffic Signal Operations

Adaptive control is an alternative to traditional coordinated control. Adaptive control uses different algorithms to alter the duration of signal phases on a cycle-by-cycle basis. Adaptive systems rely heavily on local controllers for many timing parameters and share most features of traditional systems, but provide intersection operators more flexibility in how they can adjust timing parameters to changing traffic conditions. Traditional coordinated operations are more commonly used in practice, while adaptive systems are deployed whenever advanced system capabilities are needed.

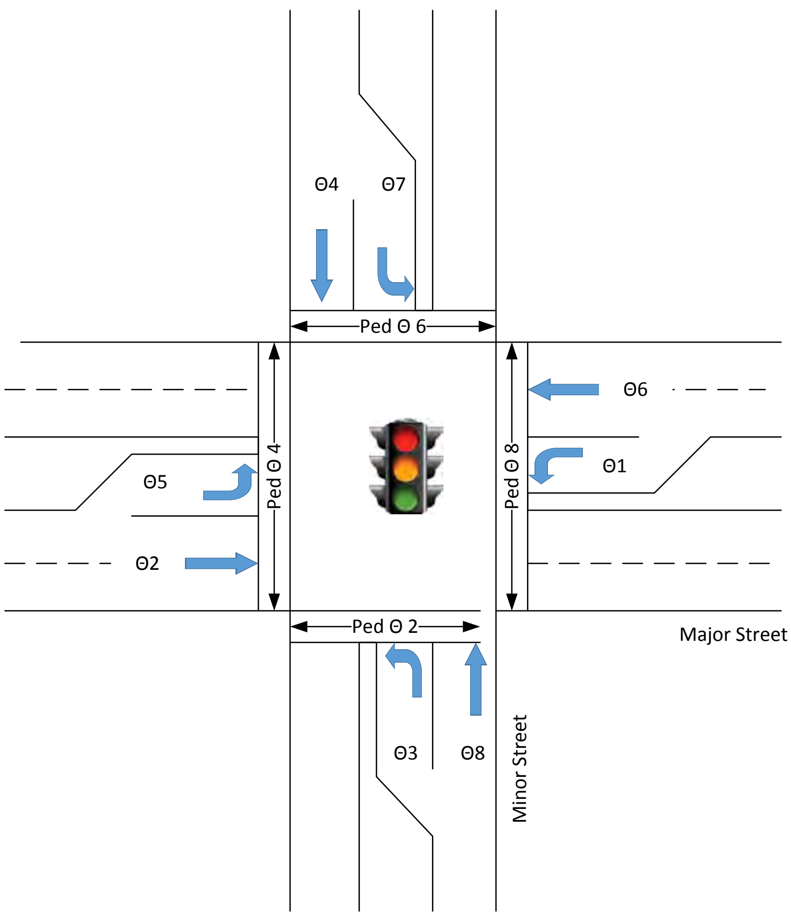
13.2 Elements of a Traffic Signal Timing

A traffic signal phase is a timing process within the signal controller that facilitates serving one or more movements simultaneously for one or more modes of users. An agency must assign phase numbers to the movements at a signalized intersection in order to begin selecting signal timing values. Many agencies use a standard number scheme developed by the National Electric Manufacturers Association (NEMA) that uses the following convention:

- Even phases are typically associated with through movements.
    - Phases 2 and 6 generally represent the major street through movements.
    - Phases 4 and 8 generally represent the minor street through movements.
- Odd phases are typically associated with left-turn movements.

    - Phase 1 and 5 generally represent the major street left-turn movements.
    - Phases 3 and 7 generally represent the minor street left-turn movements.
- Pedestrian phases are typically set up to run concurrently with the even number vehicle phases. They are generally assigned the same phase number as the adjacent, parallel vehicle phases.
    - Pedestrian Phases 2 and 6 generally represent the major street pedestrian movements.
    - Pedestrian Phases 4 and 8 generally represent the minor street pedestrian movements.

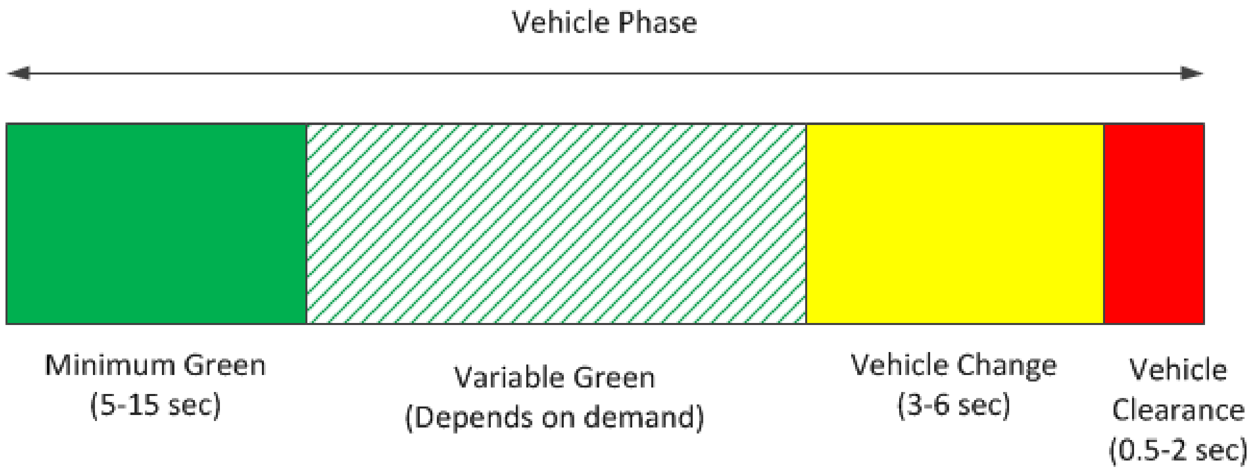
Figure 104 provides a visual representation of this numbering scheme. It should be noted that, while this numbering scheme is a generally accepted convention for matching vehicle movements with phases, some agencies have developed their own conventions for use in their jurisdiction.



Source: Texas Transportation Institute. Used with permission

Figure 104: NEMA Movement Phase Numbering Scheme

A typical traffic signal phase is divided into multiple intervals. Some of these intervals are fixed, meaning that if a phase is activated, they will 1) be guaranteed to occur regardless of traffic demands and 2) time for guaranteed duration. These intervals include the minimum green interval, the maximum green interval, the yellow change interval, and the red clearance intervals. Other intervals can vary from cycle to cycle depending upon demand. Figure 105 shows the basic intervals of a traffic signal phase.



Source: Texas Transportation Institute. Used with permission

Figure 105: Intervals within a Vehicle Phase

The green interval is actually controlled by multiple timers that run simultaneous once a phase is activated. These timers countdown from fixed, user defined parameters and dictate when a phase will terminate. These timers include the minimum green timer, the maximum green timer, and the passage timer.

The minimum green timer controls the duration of the initial green interval once it is activated. The minimum green interval is the guaranteed minimum amount of time that a phase will remain green once it has been activated. This is a fixed interval that will be displayed every time that a phase is activated. Its duration is established primarily to meet driver expectations; however, factors such as queue lengths, detector design, and pedestrian timing all influence its duration. Generally, agencies set the minimum green interval to a time between 5 to 15 seconds. Agencies will frequently set a different minimum green duration for the different phases, with left-turn phases receiving shorter minimum green duration than through movements.

The maximum green represents that maximum amount of time that a phase will remain green in the presence of a call on a conflicting phase. The maximum green timer begins timing only when there is a vehicle present on a conflicting phase (i.e., a cross-street phase). If a vehicle is not present on the cross-street, the maximum green timer will be reset to its maximum value until a vehicle is detected on the cross-street approach. This timer is intended to limit the amount of time a vehicle must wait on the cross street, while also maintaining a signal cycle length near its desired maximum time. When traffic demands are heavy on all approaches, the signal will operate like a pre-timed signal because it is consistently reaching the maximum green settings on all the approaches.

The time in the phase between minimum green and the maximum green is not fixed but can vary from cycle to cycle, depending on traffic demands. After the minimum green timer has expired, a new timer, the passage timer, takes control of timing the green indication. The purpose of the passage timer is to detect gaps in the traffic stream that represent when traffic flow has dropped below the agency’s desired level of minimum efficiency. Usually, this gap is between 1.5 and 3 seconds. The passage timer is a countdown timer that begins counting when a vehicle leaves the detection zone for the phase. If the passage timer reaches zero before a new vehicle enters the detection zone, the traffic signal controller will terminate the green phase, clear the intersection, and then proceed to the next phase (assuming there is a call for service on a conflicting phase). If, however, the controller detects that a vehicle has entered the detection zone before the passage timer has expired, it will reset the passage timer to its initial setting and begin counting down again once the vehicle has left the detection zone. As long as demand exists, the green interval will continue to extend up to the maximum green time while the passage timer is still timing. Therefore, a phase may terminate before it reaches its maximum green time when all of the following conditions are met:

- The minimum green timer has expired.
- A call for service exists on a conflicting phase, and
- The passage timer has expired.

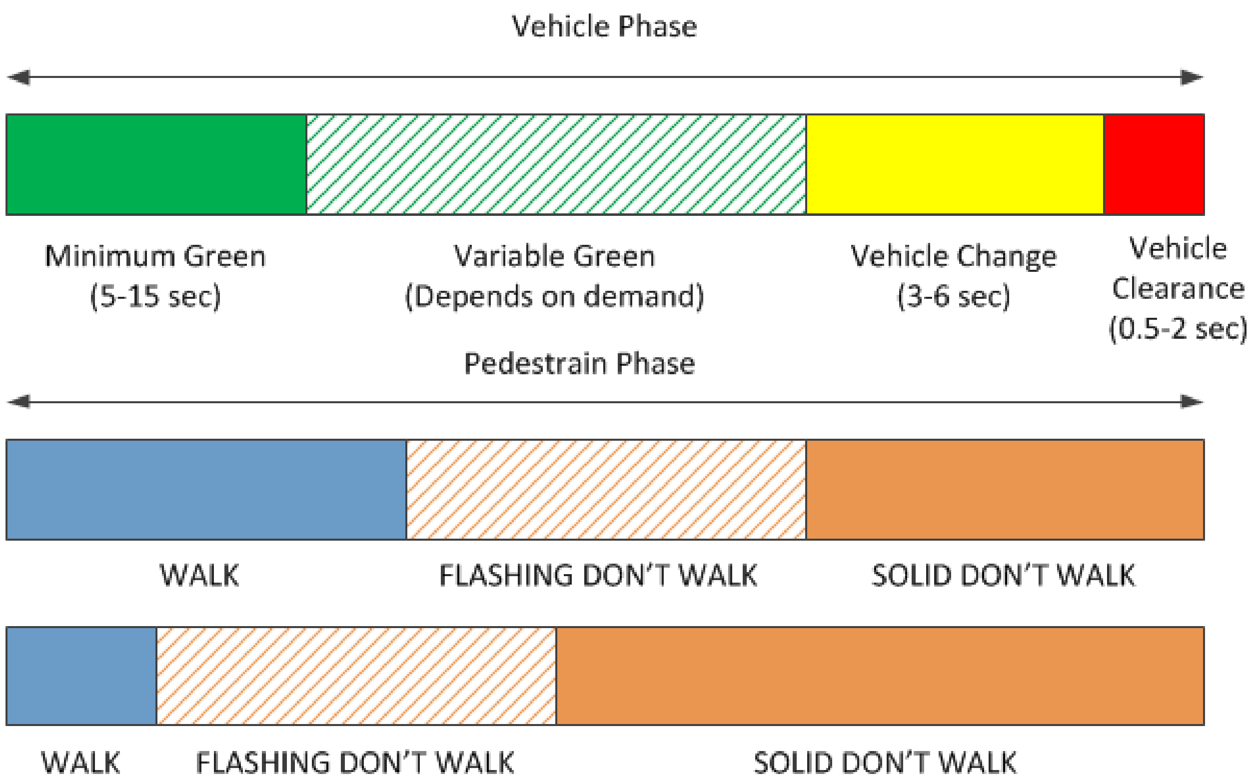
Regardless of the reason a green signal indication terminates, it will <u>always</u> be followed by a yellow change interval. This requirement is dictated by the MUTCD. The yellow change interval, also called the vehicle change interval, is the interval immediately following the green interval that warns the driver that a change in right of way assignment (i.e., a new phase) is about to occur. Depending upon the driving laws for the state in which the intersection is located, the yellow change interval can indicate that 1) a vehicle is thereby warned that the related green movement is terminated and that the vehicle must clear the intersection (this is called a *permissive yellow law*) or 2) a vehicle must stop, unless it is not safe to do so (this is called a *restrictive yellow law*). The difference in meaning influences the yellow change interval duration that an agency will set. Agencies that operate under permissive yellow laws generally will design the duration of their yellow intervals to provide sufficient warning to alert the driver of an impending change in the signal status, while agencies that operate their signals under restrictive yellow laws generally will design the duration of their yellow intervals to safely bring the vehicle to a stop at the stop bar.

The duration of the yellow change interval may vary from intersection to intersection and even from movement to movement at an individual intersection, but for any specific movement, its duration will always be the same from cycle to cycle regardless of the time of day. That is because the yellow change interval exists primarily for safety reasons and does not change based on traffic demand. The MUTCD requires that engineering practices (and not traffic demand) be used to determine the duration of the yellow change interval. The MUTCD further states that duration of the yellow change interval should be approximately 3 to 6 seconds in duration. Agencies can use longer intervals on approaches that have higher speeds; however, extremely long yellow intervals tend to encourage red light running in some drivers. Common practice among agencies is to use the Institute of Transportation Engineers (ITE) for determining the duration of the yellow interval. The ITE practice set the yellow change interval to be equal to the time required for a driver to safely stop at the stop bar of the intersection.

The last portion of a signal phase is the red clearance interval (or sometimes referred to as the "all-red" interval). The red clearance interval is that portion of the phase following the yellow change interval where a red indication is displayed briefly before displaying a green on the next proceeding phase. The purpose of the red clearance interval is to allow a vehicle that entered the intersection at the end of the yellow change interval to reach an appropriate location before the next phase is activated. The duration of the red clearance commonly ranges from 0.5 to 2 seconds. While it is common practice for agencies to use it, the red clearance interval is optional, meaning that agencies are not required to provide it at every intersection. If used at an intersection, its duration may vary from movement to movement, but remains constant from cycle to cycle regardless of traffic demands.

13.3 Pedestrian Intervals

At some intersections, the duration of the green interval for the phase is controlled by the duration of the pedestrian intervals. Pedestrian intervals are intended to control the movement of pedestrians through the intersection. Every intersection should accommodate pedestrian movements at an intersection – whether they are controlled by the vehicle movement phase or by separate pedestrian signal indications that are activated through pedestrian pushbuttons. Local practice often dictates how agencies accommodate pedestrians in their area. The relationship between the vehicle intervals and pedestrian intervals is shown in Figure 106.



Source: Texas Transportation Institute. Used with permission

Figure 106: Pedestrian Intervals

As shown in Figure 106, the pedestrian phase consists of three intervals: WALK, flashing DON'T WALK (FDW), and steady DON'T WALK. The WALK interval typically begins at the start of the concurrent vehicle green interval and is used to get pedestrians moving into the crosswalk. Its duration must be long enough for the pedestrian to notice that it has been activated, to check that no vehicles are entering the crosswalk, and to step off the curb. The MUTCD indicates that the duration of the WALK interval should be at least 7 seconds; however, in areas with high pedestrian volumes this interval can be longer. The FDW interval follows the WALK interval and is intended to inform the pedestrian that the pedestrian phase is ending. The MUTCD states that the pedestrian clearance should be sufficient to allow a pedestrian to cross at a walking speed of 3.5 feet per second from the curb or shoulder to at least a) the far side of the traveled way or b) to a median of sufficient width for pedestrians to wait. The FDW is typically the pedestrian clearance interval reduced by the yellow change and red clearance intervals. A steady DON'T WALK interval follows the FDW and is intended to serve as a "red indication" for pedestrian traffic. The MUTCD requires that a steady DON'TWALK indication be displayed for 3 seconds prior to the release of any conflicting vehicle movement phase.

13.4 Existing Red Light Violation Warning Applications

The RLVW application warns the driver if he/she is about to run a red light at an approaching signalized intersection. An RSU broadcasts MAP, SPaT, and optionally RTCM correction messages for GNSS. Refer to SAE J2735 for a definition of these messages. [15] The OBU uses the MAP and SPaT data received from the RSU plus vehicle dynamic data (e.g., position, speed, braking status, and turn signal status) to determine if a red light violation may occur. If RTCM data is available, the OBU uses it to improve its GNSS positioning accuracy.

The OBE performs the following steps:

1. Intersection Identification – Determines which intersection the OBE is approaching. The OBE may have received Map data for multiple intersections. The Intersection Identification logic selects the most likely intersection based on Map data, the OBE position, and the closure rate to the candidate intersections.
2. Map Matching – Determines if the OBE is on one of the road segments defined by the Map of the selected intersection. The Map Matching finds the minimum distance from the OBE to a lane segment, and if it is below a threshold, identifies the lane as the most probable lane.
3. Lane/Signal Group Selection – Finalizes the lane identification and identifies the applicable signal group. Due to positioning inaccuracy, the OBE may potentially be traveling in one of several lanes. In addition, multiple signal groups may apply to a lane (e.g., there are separate straight through and right turn signals). The Lane/Signal Group Selection considers driver intent (as expressed by the turn signal) and whether the vehicle is decelerating (which may indicate the applicable signal phase is yellow or red) to finalize the lane and signal group selection.
4. Violation Analysis – Determines if a red light violation is likely to occur. The Violation Analysis will not alert the driver unless the signal phase is yellow or red (based on the SPaT data for the selected lane) and the vehicle is not currently braking. The Violation Analysis algorithm is as follows:
    a. Calculates the distance to the stop bar based on the Map information and the OBE position obtained from the GNSS receiver.
    b. Calculates the time to stop bar based on the distance to the stop bar and the current vehicle speed.
    c. Obtains signal phase information from the SPaT for the selected lane/signal group. Calculates the time to red as the remaining time for the yellow phase if the signal is yellow, or zero if the signal is already red.
    d. If the signal is red or will be red before the vehicle gets to the stop bar (i.e., time to red < time to stop bar), the algorithm calculates the warning distance. The warning distance is the distance required for the vehicle to come to a complete stop, and is a function of the vehicle speed.

e. If the distance to the stop bar is less than the warning distance, then RLVW issues an alert to the driver.

Since the RLVW only alerts when the signal is yellow or red, it will work properly in the presence of fixed timing or actuated traffic signals.

13.5 Impact of Different Traffic Signal Operations on Red Light Violation Warning Applications

TTI assessed of the applicability of the existing RLVW applications under different operating modes and concluded that existing vehicle algorithm should function as intended at intersections operating under actuated control, coordinated control, or signal preemption. This is a direct result of the existing RLVW application only issuing alerts during the yellow and red portions of the signal phase. The yellow clearance interval is a fixed interval and does not vary from cycle to cycle, irrespective of the operating mode of the traffic signal. Consequently, once the yellow interval has started, the onset of the red interval can be accurately and consistently predicted regardless of the traffic signal operating mode. If future application or calibration changes result in alerts being issued prior to the beginning of the yellow phase (i.e., when the traffic signal is still displaying a green indication) the application's functionality will be negatively impacted due to the uncertainty in the duration of the green phase. As discussed previously, a number of factors can cause the green interval to vary. These include:

- The presence and proper functionality of detection at an intersection.
- The presence of and the duration that cross street traffic has been waiting at the intersection.
- The time gaps that exist between vehicles on the main street approach.
- The operating mode of the traffic signal controller (i.e., whether the intersection is operating in a "free" mode or under coordinated control.
- The duration of the green interval for the coordinated phase.
- The need to satisfy high priority vehicles, such as trains and emergency vehicles.

These factors confound the ability to accurately predict the end of the green interval of any one particular signal phase with a reasonable level of confidence. However, once the phase begins to terminate (i.e., the yellow clearance interval is displayed), the controller will remain in the yellow clearance interval for a fixed duration, regardless of the operating mode of the controller.

14 CSW and RSZW Engineering Testing on Public Roads

This chapter describes the engineering testing on public roads for the CSW and the RSZW/LC applications. Multiple on-road tests were conducted in Southeast Michigan to evaluate the performance of the two applications which could not be done at the test track. (Objective testing was discussed in Chapters 10 and 11).

The objective of the CSW on-road test was to assess overall performance of the algorithm in real-world driving on multi-radii curves and to verify appropriate generation of Inform and Warning(s) for curve radii calculated using the node-by-node method. While in the RSZW, the objective was to evaluate the work zone warning application on a real work zone.

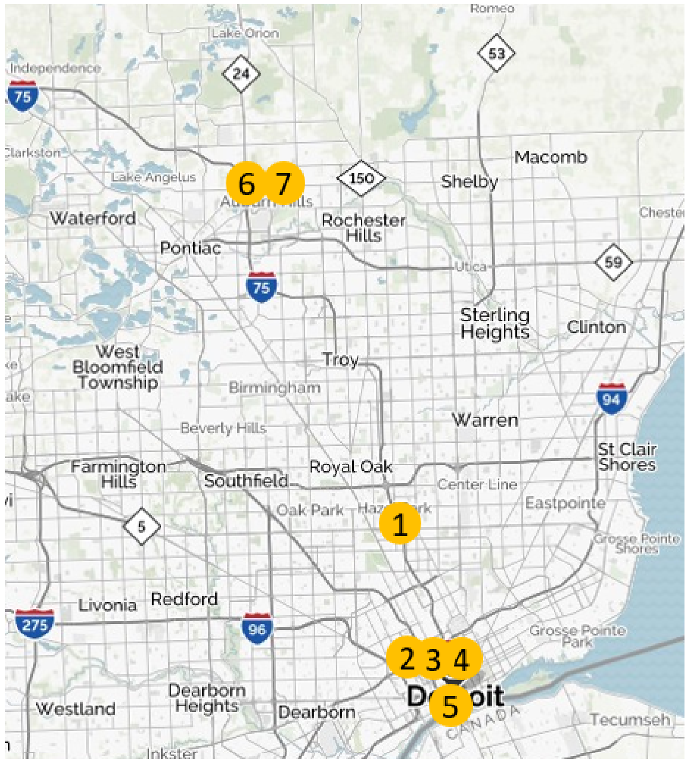
The infrastructure equipment built in the project (see Chapter 9) and the project test vehicles (see Chapter 8) were used in this effort. The vehicles were driven by professional test drivers. The test plans, including test locations, were developed along with data collection procedures. A comprehensive analysis of the data collected during the on-road tests was conducted and the application performance analysis is described in following subsections. The on-road testing for CSW is described in Section 14.1, while Section 14.2 presents the details and findings of the RSZW/LC on-road tests.

14.1 CSW On-Road Testing

The on-road tests of CSW were conducted on multiple curves in Southeast Michigan. Seven curves were selected to conduct the field test. The selection criteria were based on different factors to cover most curvature characteristics and acute curves in the area, which are defined as follow:

- Simple and moderately complex curves consisting of single and multiple radii curves
- Varying radii from large radius to small radius on the same curve
- S-curves – left-hand and right-hand curve
- Normal entrance and exit ramps for freeway
- Interchanges between freeways

The objective of the on-road tests was to validate the performance of the application in real-world scenarios. Figure 107 shows the location of each selected curvature for testing. The seven selected curvatures vary in complexity, radii, shape and location.

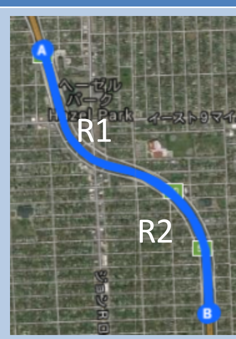


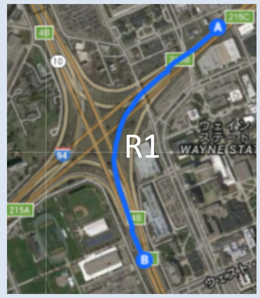
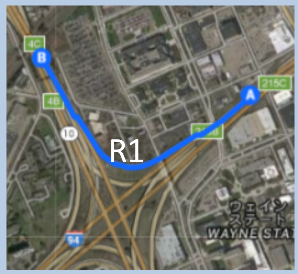
Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 107: Location of Selected Curves for On-road Testing of CSW

Detailed characteristics for each curve are illustrated in Table 35. The table shows the curve number, location, shape, radii and the calculated maximum speed V_{max} for every radius in the curvature.

Table 35: Characteristics of Selected Curves with Calculated V_{max}

Curve No.	Location	Curvature	Radius	V_{max}
1	I-75 Southbound at 9 Mile Road		R1 = 466 m R2 = 661 m	$V1_{max}$ = 114 mph $V2_{max}$ = 135 mph

Curve No.	Location	Curvature	Radius	V_{max}
2	I-94 Westbound to M-10 Southbound Interchange		R1 = 377 m	V_{max} = 99 mph
3	I-94 Westbound to M-10 Northbound Interchange		R1 = 129 m	V_{max} = 58 mph
4	I-94 Eastbound to I-75 Northbound Interchange		R2 = 125 m R1 = 450 m	$V2_{max}$ = 57 mph $V1_{max}$ =108 mph
5	I-75 Southbound W to M-10 Southbound Interchange		R1 = 429 m R2 = 65 m	$V1_{max}$ = 106 mph $V2_{max}$ = 41 mph
6	Lapeer Rd. Northbound Ramp to I-75 Freeway		R2 = 90 m R1 = 156 m	$V2_{max}$ = 48 mph $V1_{max}$ = 64 mph

Curve No.	Location	Curvature	Radius	V_{max}
7	I-75 Business to I-75 Southbound		R2 = 73 m R1 = 200 m	$V2_{max}$ = 44 mph $V1_{max}$ = 71 mph

Source: Map images from Google. Used with permission. Data from CAMP – V2I Consortium

The V_{max} calculation for all the seven curves is based on node-by-node radius calculation as discussed previously in Section 6.3.2. For each node, the V_{max} (the vehicle safe speed to travel on that curve) calculation is based on two different parameters. One is the centripetal force and the other one is the stability force. The lower of the two computed values is used to determine the V_{max} (see Section 6.3.2.3).

For all selected curves, the parameters used to calculate the V_{max} are as follows:

- Roadway material: concrete
- Roadway surface condition: dry
- Superelevation of the curve: 5°
- Friction of coefficient µ of the curve: 0.65
- Factor of safety: 0.65

14.1.1 Analysis of Conducted CSW Tests

For each curve, a curve geometry was developed. Because all the seven curves are non-uniform curves, the curve geometries were defined using the node segments which have varying curvature. For each node segment, the application determines the radius of the curvature, then determines the warning(s) for each node. The uniform warning can be achieved, depending on the speed and the location (i.e., the node segment) of the vehicle on the curve.

A utility tool was created to visualize the behavior of the CSW application and to analyze the data collected by the test vehicles. The tool allows an analyst to replay logged data and generate plots of the collected data from a specified road overlaid on a roadway map from Google Earth. For each data element, the plot shows the vehicle behavior, including map matching, vehicle speed, node segment and radius of the segment, and generated inform and warning messages. Different colors were used to identify the state of the vehicle and the CSW application as follows:

- Purple dots: indicate the vehicle is outside of the mapped geometry
- Black dots: indicate no map matching and in “geometry retry” state

- Yellow dots: indicate the state when the vehicle receives Inform message for a curve ahead
- Orange dots: indicate Warning1 (vehicle on geometry and the vehicle speed is above the computed Vmax speed)
- Red dots: indicate Warning2 (vehicle on geometry and the vehicle speed is above the computed V_{max} speed and immediate driver action is required)
- Green dots: indicate the vehicle is on the mapped area and the speed is below the computed V_{max} speed.
- Blue arrow: indicate test vehicle direction of travel.

For each on-road test run on the selected curves, the data was analyzed and checked to evaluate the system performance. The following subsections present a detail study for each curve. The plots shown were produced by the utility tool and contain the color coding described above. In all, three test vehicles were used on different days and times to conduct the 74 test runs, as shown in Table 36.

Table 36: Conducted Test Runs

Test Vehicle	Curve #1	Curve #2	Curve #3	Curve #4	Curve #5	Curves #6 & #7	Total
Audi	–	–	14	16	6	11	47
Buick	–	–		–	–	10	10
Hyundai-Kia	–	–	17	–	–	–	17
Total	–	–	31	16	6	21	74

Source: CAMP – V2I Consortium

14.1.1.1 Test Curve #1 and Curve #2

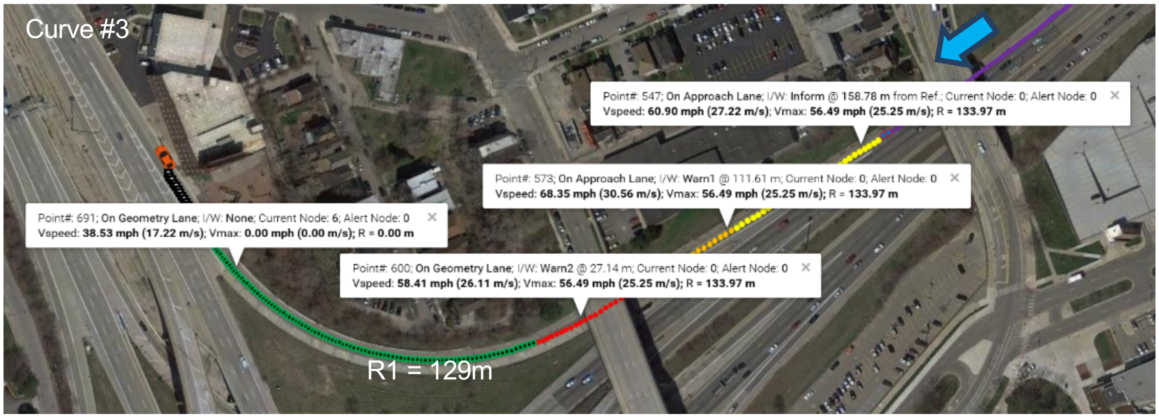
Curve #1 is located at I-75 Southbound and 9 Mile Road. This curve, identified as an S-curve, consists of a left-hand and right-hand curve. The left-hand curve has a radius of R1= 466 m, and the right-hand curve has a radius of R2 = 661 m. However, the calculation of the V_{max} defines the safe speed for vehicle to travel on the left-hand curve as $V1_{max}$ = 114 mph, and the safe speed for vehicle to travel on the right-hand curve as $V2_{max}$ = 135 mph. Since both V_{max} values are above the roadway speed limit, this curve was not used for the tests.

Similarly, curve #2 is located at the interchange between I-94 Westbound to M-10 Southbound. This curve has single radius of R1 = 377 m. The V_{max} calculation specified the safe speed as of V_{max} = 99 mph. The on-road test for this curve also was not conducted due to the high value of the V_{max} and the need to go over the posted speed limit to evaluate the application.

14.1.1.2 Test Curve #3

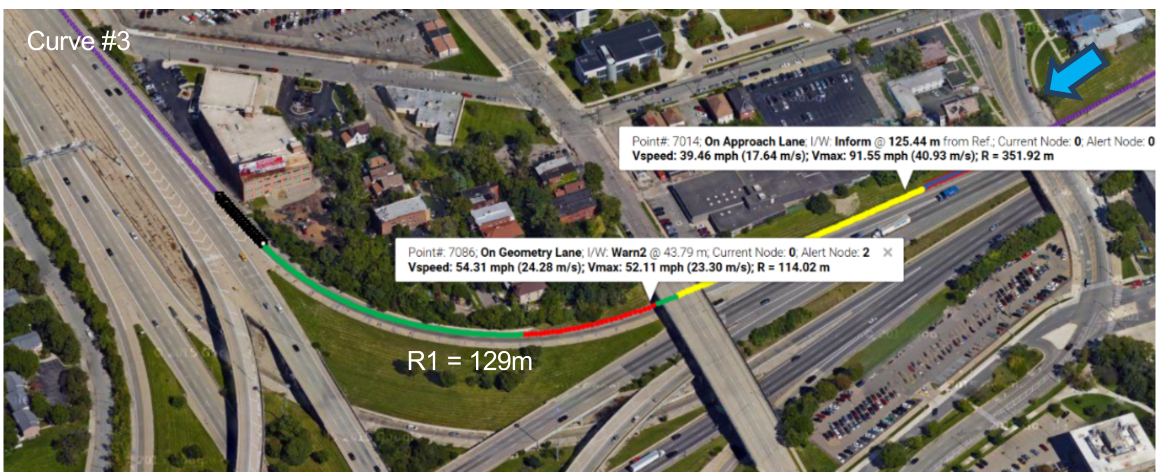
This curve is located near the downtown area of Detroit, at the I-94 Westbound to M-10 Northbound interchange. It is a single radius curve of R1 = 129 m and the computed V_{max} speed for the curve is V_{max} = 58 mph.

On October 4, 2016, the Hyundai-Kia test vehicle was used to conduct 17 test runs and on October 18, 2016, the Audi test vehicle conducted 14 test runs on curve #3. The vehicles approached the curve at different speeds since the tests were conducted during different times of the day and encountered varying traffic conditions. In several test runs when the traffic was heavy, the test vehicles could not attain a speed high enough to trigger a warning. Figure 108 and Figure 109 depict the behavior of the application in two different test runs where the Inform and Warning messages were generated as expected. The blue arrows show the vehicle's direction of travel.



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 108: Test Curve #3, Test Vehicle – Hyundai-Kia Test Run 1



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

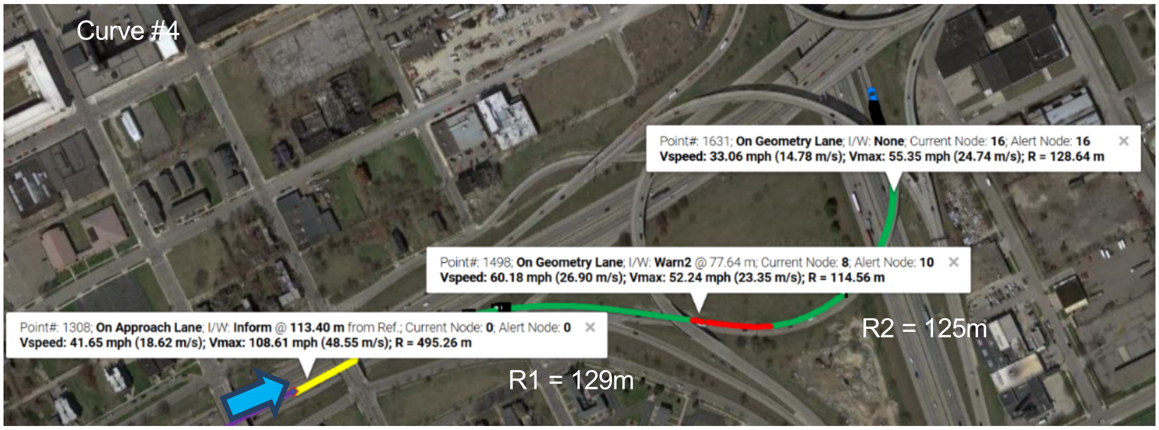
Figure 109: Test Curve #3, Test Vehicle – Hyundai-Kia Test Run 2

14.1.1.3 Test Curve #4

This curve is located at the I-94 Eastbound to I-75 Northbound interchange in downtown Detroit. The curve has an S-shape. The right-hand curve has a radius of R1 = 450 m which gives a $V1_{max}$ = 108 mph while the left-hand curve has a radius of R2 = 125 m and a $V2_{max}$ = 57 mph.

On October 18, 2016, the Audi test vehicle was used to conduct 16 test runs on curve #4. Figure 4 represents the application behavior for a test run that generated appropriate Inform and Warning messages as expected. As shown in Figure 110, the vehicle approach speed was about 40 mph. An

Inform message was generated within 114 m from the reference point, which indicates the beginning of the curve. Only one warning (Warning 2) was generated when the V_{speed} is 11 mph or less above the computed V_{max}, as in this case V_{speed} = 60.18 mph and the V_{max} = 52.24 mph. The warning was suppressed when the V_{speed} dropped below V_{max}.



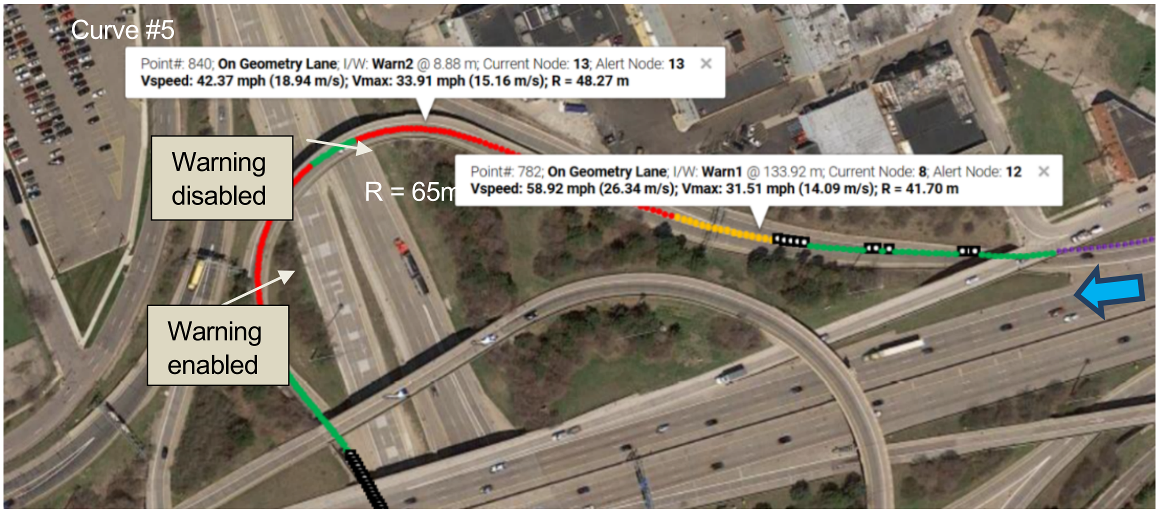
Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 110: Test Curve #4, Test Vehicle - Audi

14.1.1.4 Test Curve #5

Curve #5 is located at the I-75 Southbound west to M-10 Southbound interchange close to downtown Detroit. This curve starts with a right-hand curve with a radius of R1 = 429 m and $V1_{max}$ = 106 mph. This curve is followed by a left-hand curve with a radius of R2 = 65 m and V2max = 41 mph. The curve geometry and the warning calculations were based on the node segments.

On October 18, 2016, the Audi test vehicle was used to conduct six test runs on curve #5. The algorithm generated Inform, Warning 1 and Warning 2 as expected. The algorithm also disabled the warning when the V_{speed} dropped below computed V_{max} for the node segment and enabled them again when the V_{speed} was above the V_{max} for the node segment. Figure 111 shows details from a test run. Warning 1 followed by Warning 2 were generated appropriately as the V_{speed} was higher than calculated V_{max} of the node #12.



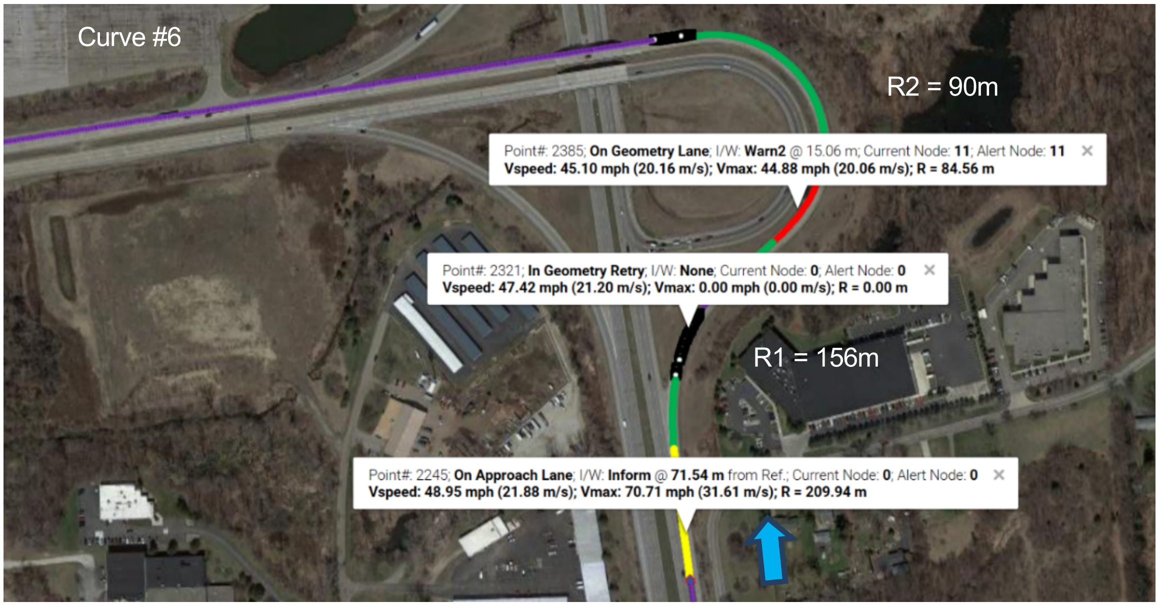
Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 111: Test Curve #5, Test Vehicle - Audi

14.1.1.5 Curve #6 and #7

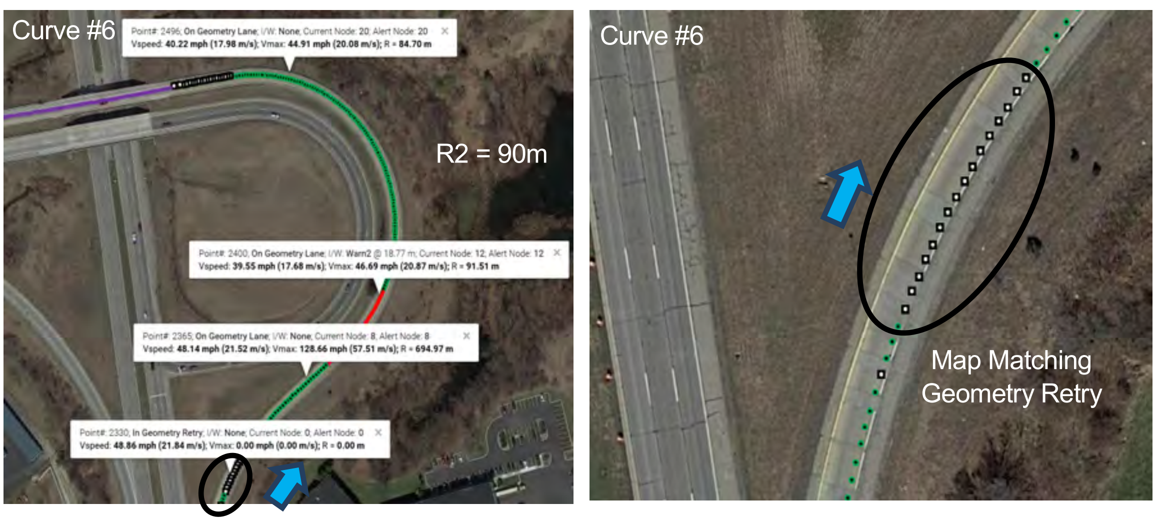
The curve #6 is located at the Lapeer Road ramp to I-75 Northbound in Auburn Hills. This curve is a loop-shaped curve, consisting of a right-hand curve with a radius of R1 = 156 m and $V1_{max}$ = 64 mph, and a left-hand curve with a radius of R2 = 90 m, $V2_{max}$ = 48 mph. Curve #7 is located on I-75 Business, leading to the I-75 Southbound freeway immediately after curve #6. Curve #7 is loop-shaped with two right-hand curves changing from a large radius curve (R1 = 200 m, $V1_{max}$ = 71 mph) to a small radius curve (R2 = 73 m, $V2_{max}$ = 44 mph). Curve geometry is defined using node segments and V_{max} is calculated for each node.

Two different test vehicles (i.e., Audi and Buick vehicles) were used to conduct 21 test runs on October 18-19, 2016. The CSW algorithm performed as intended on both curves for both test vehicles in various approach speeds between 40 and 67 mph. Figure 112 shows behavior of the CSW algorithm on curve #6 for the Audi test vehicle in which Inform and Warning were generated as expected. In Figure 113, an anomaly discovered on curve #6, related to map matching in one of the test runs with the Audi, is shown. The cause and resolution of the map matching issue is described in analysis of the CSW test results in Section 14.1.2.



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

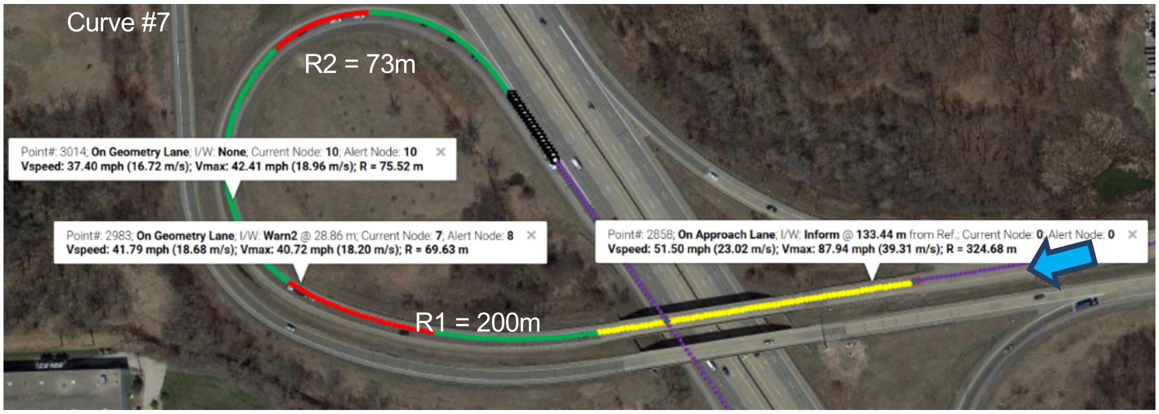
Figure 112: Test Curve #6, Test Vehicle - Audi



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

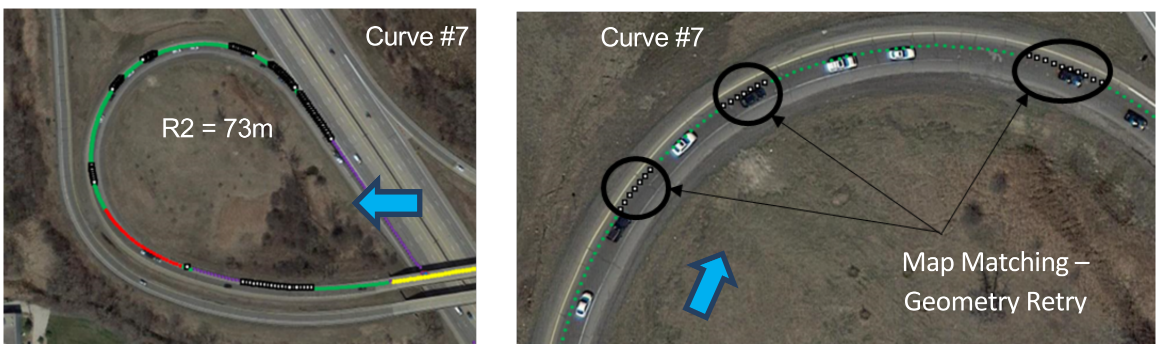
Figure 113: Test Curve #6, Test Vehicle – Audi, “Geometry Retry”

Figure 114 shows the behavior of the CSW algorithm on curve #7 for the Buick test vehicle in a run in which Inform, Warning1 and Warning 2 were generated as expected. Figure 115 shows a map matching anomaly for the Buick on the curve #7 while Figure 116 shows another test run on curve #7 where the warning was discontinued due to the map matching anomaly when the vehicle went out of the mapped lane. The cause and resolution of the map matching issues identified during testing are described later in the analysis of on-road CSW test results (see Section 14.1.2).



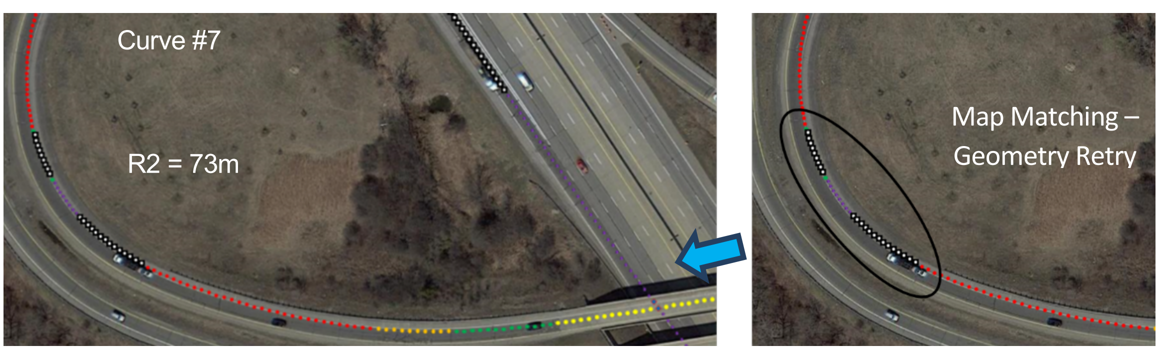
Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 114: Test Curve #7, Test Vehicle - Buick



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 115: Test Curve #7, Test Vehicle - Buick, "Geometry Retry"



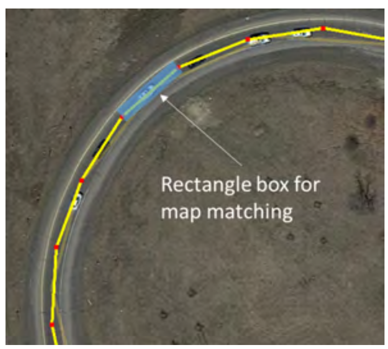
Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 116: Test Curve #7, Test Vehicle - Buick, "Geometry Retry," Warning Discontinued

14.1.2 Analysis of CSW Test Results

When analyzing the CSW data collected from all test runs, anomalies related to map matching were discovered. In some scenarios, when the vehicle traveled on a curve with a small radius value and at a lower speed, the driver tended to drive on either edge of the curve or on the shoulder area. However, the CSW bounding box algorithm for map matching may not include the shoulder area as part of the lane geometry. Consequently, when the vehicle travels outside of the mapped geometry, the vehicle is outside of the map matching zone causing a "geometry retry" as shown in Figure 113 for curve #6 in the Audi test run. As the test vehicle was driven on the edge of the lane, it went out of the map matching zone. Similarly, for curve #7 the map matching issue was identified in the Buick test run in Figure 115. The warnings were discontinued when the vehicle went out of the mapped lane as shown Figure 116.

Further analysis of the collected data and the mapped lanes for the curve indicated that the lane width specified for the curve lane was the same lane width that was used for the lane approaching the curve. In actuality, the lane width of the curve lane is wider than the approach lane width. The actual lane widths for curve #6 and curve #7 were 4.2 m and 4.7 m, respectively, while the lane width specified in the map was 3.76 m for both of the curves. As shown in Figure 117, the map matching algorithm creates a rectangular bounding box, which identifies a map matching zone for each node segment based on the specified lane width for the curve in the map. The constructed bounding box for the curve lane was smaller in width (height). Thus, when a vehicle was close to edge of the lane, it was positioned outside the bounding box, causing the observed failures in map matching.



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 117: Rectangular Bounding Box for Map Matching Zone

Two other factors may cause variation in the construction of rectangular bounding box for the mapping zone. These factors are the variation in the width of the lane throughout the curve and placement of nodes for curve geometry. Based on the test analysis, compensation for such variations can made by adding a configurable "lane width padding" in the algorithm for the curvature lane.

14.2 RSZW/LC On-Road Testing

The test sites for evaluating the work zone application were selected in conjunction with MDOT. The on-road testing for RSZW/LC was planned for the 2016 road construction season. The construction season in Michigan is approximately from April – December. The goal of the tests was to evaluate the RSZW/LC application under various combinations of conditions selected to produce warnings for assessment when the vehicle was travelling in a work zone. Test conditions included variations in vehicle travel speeds, types of lane closures, and the presence or absence of workers in the zone. Details of the RSZW/LC on-road testing are presented in the following subsections.

14.2.1 Identified Work Zones for RSZW/LC On-road Tests

Three work zone areas were considered for testing.

1. The first work zone identified was located on Northbound I-275 (at M5 to I-96). However, the on-road testing on this work zone was not conducted due to complete freeway closing at the construction area. The northbound lanes closed first, followed by the closure of the southbound lanes, making this site unsuitable for testing.
2. The second work zone was located on the I-94 (Telegraph Rd to I-275). Construction at this site was held during nights and weekends. Unfortunately, the testing was not conducted in this area, because the required trailer and RSU could not be made available while the construction work was ongoing.
3. The third work zone identified was located on Southbound I-75 near M-59 in Auburn Hills. The RSZW/LC on-road test was conducted at this location.

14.2.2 Evaluation of Work Zone Area

The construction area was located on Southbound I-75, North of M-59 to Coolidge Road, where the left lane of the freeway was closed. This area is a four-lane freeway with a normal speed limit of 70 mph and the work zone speed limit of 60 mph. The speed limit drops to 45 mph when workers are present (Michigan state law).

The work zone map was made by MDOT, under the direction of the V2I-SA TMT, using Google Earth since the surveyed work zone map was not available. The mapping of the work zone consisted of three major elements:

- The approach lanes leading to the construction zone
- The work zone lanes with the reference point indicating the start of the work zone
- The offset for the start of lane closure from the reference point

Figure 118 shows the work zone map using Google Earth. Approach lanes indicated by white lanes continue through the work zone indicated by blue lanes. The left approach lane shown by the light cyan color closes in the work zone. The closed lane in work zone is shown in red. The taper for the lane closure starts at the reference point. In this case, the offset for the start of the lane closure from the reference point is zero.

Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 118: RSZW/LC Work Zone Map

By late November, MDOT completed programming of the RSU with the work zone map and the work zone speed limits. This effort was guided by the SA-V2I TMT. The RSU was mounted on a trailer about 20 feet above the ground and the trailer was placed near the work zone on the right side of the roadway (i.e., along I-75 south of the University Drive exist ramp, as shown in Figure 119). The placement of the RSU provided clear line-of-sight for the test vehicles to receive the work zone DSRC messages.

The first available opportunity to conduct testing was in early December 2016. Workers were not present during the tests although lane closure was still in effect. Based on the work zone configuration, the work zone speed limit was 60 mph.

Source: CAMP – V2I Consortium

Figure 119: Mounted RSU Near the Work Zone

14.2.3 RSZW/LC Test Scenario

On December 7, 2016, the RSZW/LC on-road test was conducted using the Hyundai-Kia and Audi test vehicles. Each vehicle was driven by a professional driver and each vehicle conducted four test runs, one run on each lane of the work zone. The Audi vehicle conducted one additional test run to verify the functionality of the RSU prior to the testing session. Overall, nine test runs were conducted for the following test scenarios:

- Lane Closure: The test vehicles travelled on the approach lane that is closed ahead in the work zone and received inform and warning for lane closure as expected. The warning was suppressed when the turn signal was turned on indicating the driver is aware of the situation and ready to change lane. Also, when the lane change was performed, the lane closure was disabled as expected.
- Reduced Speed: The test vehicles travelled above the posted speed limit in the work zone area (60mph, no workers present). The vehicles received a warning as intended.
- Speed Variation: The mapped work zone length was not long enough to conduct the speed variation test. The work zone was about 330 m long and required less than 12 s to traverse at 60 mph. Consequently, the work zone speed violation, and warning suppression and generation could not be evaluated.
- Throughout the work zone, the test vehicles continuously received an Inform message until the vehicle was out of the work zone mapped area, as designed in the algorithm. The Inform message indicated the vehicle was travelling in a work zone area.

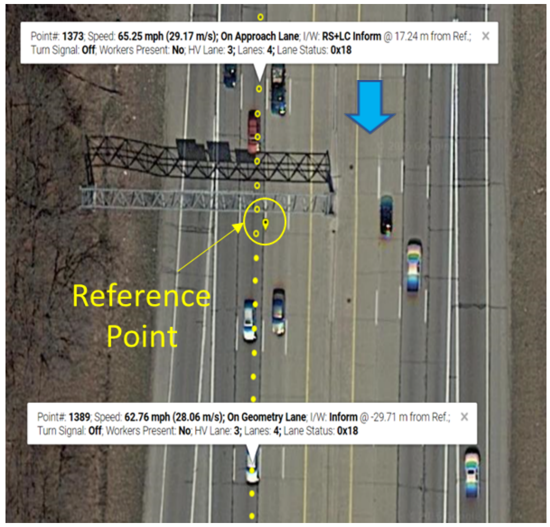
14.2.4 RSZW/LC Test Evaluation

To evaluate the RSZW/LC application performance, a utility tool was developed to visualize the data collected by test vehicles. This tool can plot all the collected data on a map of the road using Google Earth. Each data point a description of the vehicle state such as map matching, vehicle speed, worker presence (yes/no), turn signal status (on/off), current lane number, total number of lanes on the road, lane status (closed/open), and generated Inform/Warning. Different colors were used to identify the state of the vehicle and the RSZW/LC application as follows:

- Black dots: indicate no map matching and in a “geometry retry” state
- Yellow dots: indicate inform of work zone ahead
- Orange dots: indicate warning of lane closure ahead
- Red dots: indicate warning of a reduced speed zone (i.e., vehicle speed greater than the posted speed limit)
- Blue arrow: indicates the vehicle travel direction

To validate the application performance, the collected data from all test runs were analyzed. The data analysis indicated that the application worked as intended and that the Inform and Warning for the lane closure and reduced speed work zone area were generated as expected. However, the analysis identified some anomalies. The causes and resolutions of the anomalies are discussed in the RSZW/LC analysis found in the next section of the report.

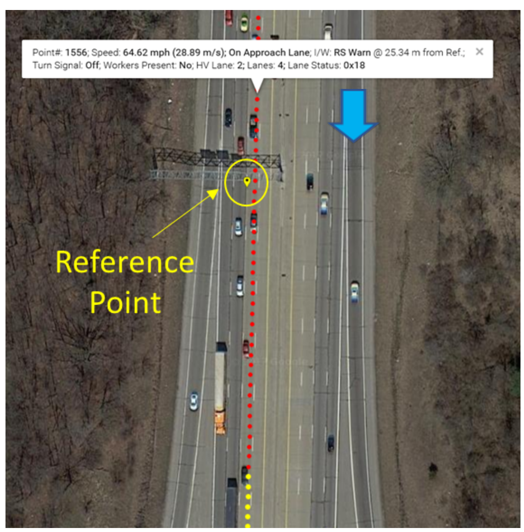
Figure 120 shows the collected data and the application performance during the on-road test, when the vehicle was driven on the left-most lane approaching the work zone (i.e., the lane that is closed in the work zone). In this test run, the vehicle speed was less than work zone speed limit (60 mph), and the appropriate lane closure warning was generated as expected.



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 120: Test Vehicle Driven on the Left Most Lane (Closing Lane)

Figure 121 illustrates the application behavior when the test vehicle was driven on the left center lane. In this scenario, the vehicle speed was over the work zone speed limit (60 mph) and the Reduce Speed warning was generated. In addition, when the test vehicle was driven on the center-right and right-most lanes, appropriate Inform and/or Warning were generated as anticipated.



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

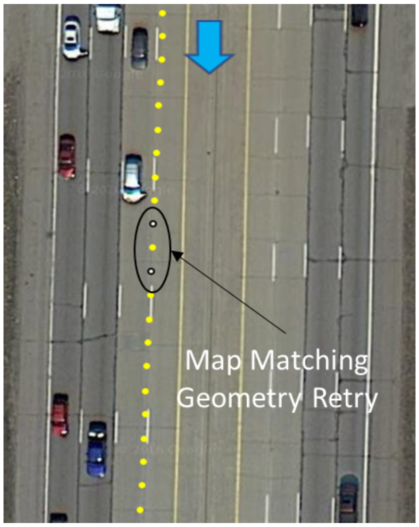
Figure 121: Test Vehicle Driven on the Left Center Lane

14.2.5 Analysis of RSZW/LC Test Results

During the process of analyzing collected data from the test vehicles, two issues were identified. The first issue noted was the location of generated Inform/Warning messages. The generation of these messages is based on the reference point. For this test site, over a month elapsed between the time the work zone map was generated and the time the prepared RSU was positioned on site. During that time, the start of lane closure moved and the RSU did not receive a map update to reflect this change. The resulting discrepancy is indicated by the reference point shown in Figure 120 and the irregularity in plot of the collected data. This affected the location of the generated Inform (15 s) / Warning (10 s) messages.

As shown in Figure 120, the vehicle continued to drive on the closing lane primarily because the lane closure was moved about 150 m south from the original mapped location. In this case, the generated Inform and Warning provided about an additional 5 s. On the other hand, if the reference point was moved to the north, the generated Inform and Warning would have been late and may not provide enough time for the driver to take appropriate action. One of the questions in deploying a real-world work zone warning application is how to accommodate changing reference point locations as construction progresses without the need to remap the work zone.

The second issue observed was the map matching retry while the vehicle is changing lanes and on the lane marker. Figure 122 shows the map matching “geometry retry” in two data points where the vehicle is changing from one lane to the next. This is caused by the varying lane widths in the real-world. To address varying lane width, a configurable “lane pad” parameter is used in the algorithm for map matching. By adding a lane padding value of 0.5 m or less in this case, the map matching was resolved and the algorithm did not go into a“geometry retry” state.



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 122: Map Matching “Geometry Retry” While the Test Vehicle is Changing Lane

15 Summary

This report describes the work conducted by the Vehicle-to-Infrastructure Safety Applications Project to design, develop, test and demonstrate three V2I safety applications. This work was contained within Tasks 1 through 12 of the project and conducted from project inception in September 2014 through June 30, 2017. The applications were integrated into six passenger vehicles and one heavy-duty truck, which served as the prototype test vehicles for the project. In addition, prototype infrastructure equipment was also developed to facilitate testing of the applications. The work was conducted by the V2I Consortium through FHWA Cooperative Agreement DTFH611H0002, Work Order 0003.

Application Selection and Development

Initial work in the project focused on a technical assessment of five applications: RLVW, SSGA, CSW, SWIW and RSZW. The technical assessment of the safety applications included a review of the prior systems engineering work conducted for FHWA and rendered an OEM-perspective regarding the implementation feasibility, benefits, and issues concerning coexistence of multiple applications. Selection criteria based on V2I deployment attributes and project impact were developed. The AASHTO National Connected Vehicle Field Infrastructure Footprint Analysis document [1] was reviewed to support the selection of applications. Three applications (RLVW, CSW and RSZW-LC/RS) addressing intersections, vehicle speed, and localized traffic variances were selected as pilot applications for further investigation.

The V2I Consortium developed a work plan, cost estimates for development, integration and evaluation of the three selected applications, a set of requirements for the in-vehicle and infrastructure systems architecture, and coordination plans for the selected suppliers. The algorithms developed during this stage of the work were designed to work for both light- and heavy-duty vehicles. Another significant outcome from this effort was the design and development of an infrastructure-based DSRC OTA message called the Basic Information Message (BIM). The overriding purpose of the BIM was to facilitate the transmission of the safety application data elements via a single, flexible message, which could be extended to accommodate future applications.

The three safety applications were implemented, and the in-vehicle software and hardware elements were integrated into the test vehicles. The necessary testing of the on-board software/hardware systems was done to ensure correct functionality on the vehicle side.

Temporary, portable infrastructure equipment for use at test locations was also developed during the project. The infrastructure equipment included an RSU with portable power supply, traffic signals, traffic signal controller and a GPS base station for RTCM correction. The BIM developed in the project was implemented in the RSU. Updates to the RSU/BIM were made as needed to support testing at several different locations and also to incorporate changes to the SAE J2735 standard that occurred during the project.

Application Testing, Evaluation and Refinement

Testing the safety applications and BIM involved both on-road and test track work. More than two dozen distinct test scenarios were designed and a more than one hundred test runs were conducted over a period of eleven months. The test scenarios were modified as required to incorporate the vehicle dynamics associated with heavy vehicles. Multiple test runs were conducted on metropolitan roads near the CAMP office in Farmington Hills, Michigan. Various road surfaces and conditions, superelevations, and lane closures were simulated in the infrastructure-based BIM during testing. Analyses of test data and technical discussions helped refine the parameters of the algorithms.

Subsequently, Objective Test Procedures were designed and conducted at the FTTA Proving Ground in Fowlerville, Michigan for consistent, repeatable tests. During two rounds of testing in November 2015 and in February 2016, different aspects of application algorithms were validated and parameters were refined to achieve desired performance. The dynamic pad at the test track enabled testing of CSW on curved roads with single- and dual-radii, while a straight section of the test track was used to test the RSZW/LC and RLVW scenarios with multiple lane closures and intersections, respectively.

With regard to all vehicle types, the data analysis phase provided an overall verification of the algorithms as designed. Through a detailed analysis of the data from the objective tests, the RLVW and CSW algorithms were refined and additional tests were conducted at the test facility at the University of Michigan in Ann Arbor, Michigan to validate their performance. Most notable among the outcomes from objective testing were:

- The RLVW algorithm was enhanced to support a single lane that can be associated with multiple signal phases for multiple movements.
- The CSW application was modified to generate a single warning to alleviate the occurrence of second warning less than a second apart from the first, a circumstance that was noted during testing when the vehicle speed only slightly exceeded (11 mph or less) the computed speed for a curve.
- With regards to the infrastructure, it was identified that the internal clock of the RSU be synchronized to the UTC time and the system clock be accurate within 10 ms of the UTC reference time in order to provide correct operation of RLVW and other applications.
- Adjustments were needed in the construction of the BIM, including:
    - The arrangement of latitude and longitude “waypoints,” to define lane geometry with respect to the reference point used in the BIM and the defined approach classification in construction for CSW.
    - For RSZW/LC, all approach lanes that logically connect to one or more geometry (work zone) lanes shall specify this connection through the “connectsTo” data frame as defined by the SAE J2735 standard.

In the case of commercial vehicles, the data analysis also verified the need for early alert messages based on stability criteria (for CSW), and thus the need to execute in real-time the stability evaluation simultaneously with the traction evaluation. This was demonstrated in testing on the highway and the proving grounds in situations where the traction-loss threshold speed was far in excess of the “rollover” (stability) threshold speed. The data analysis further underscored the differences in vehicle dynamics for heavy-duty vehicles with respect to light-duty vehicles, exposing the need to configure the deceleration capability for a given size vehicle, due to its effect on the timing of the Warnings issued to the driver.

Engineering testing of CSW on public roads and RSZW/LC in a live work zone were also conducted during the project. In CSW testing, anomalies related to map matching were discovered especially when the curve has a small radius and the vehicle is traveling on the edge of the lane or on the shoulder area. The CSW bounding box algorithm for map matching may not include the shoulder area as part of the lane geometry. Two factors that may cause variations in the construction of rectangular bounding box for the mapping zone are the variations in the width of the lane throughout the curve and placement of nodes for curve geometry. Compensation for both of these artifacts can be made in the algorithm by adding a configurable “lane width padding” for the curvature lane.

During the analysis of data from the on-road RSZW/LC testing, two issues were identified, leading to further refinement of the application. The first issue concerned the location of the generated Inform/Warn message, which is based on the location of the reference point indicating the start of the work zone or lane closure. During the on-road RSZW/LC tests, the reference point shifted by about 100 m in the actual work zone but the transmitted DSRC BIM was not updated to reflect the change. This discrepancy affected the location at which the alert for the driver was generated and highlights the need to provide maps that match the actual roadway configuration. The second issue involved map matching attempts when the vehicle was changing lanes and was on the lane marker. This issue can be attributed to the varying lane width, a condition typical in real-world settings. This latter issue was resolved by padding the lane width parameter.

Subsequently, the team assessed the current implementation of RLVW under different operating modes of traffic signals, and concluded that the existing vehicle algorithm should function as intended at intersections operating under actuated control, coordinated control, or signal preemption. This is a direct result of the existing RLVW application only issuing alerts during the yellow and red portions of the signal phase. The yellow clearance interval is a fixed interval and does not vary from cycle to cycle, irrespective of the operating mode of the traffic signal. Consequently, once the yellow interval has started, the onset of the red interval can be accurately and consistently predicted regardless of the traffic signal operating mode. If future application or calibration changes result in alerts being issued prior to the beginning of the yellow phase (i.e., when the traffic signal is still displaying a green indication) the application’s functionality will be negatively impacted due to the uncertainty in the duration of the green phase. A variety of factors can cause the green interval to vary and can make the prediction of the end of the green phase more challenging. However, once the phase begins to terminate (i.e., the yellow clearance interval is displayed), the controller will remain in the yellow clearance interval for a fixed duration, regardless of the operating mode of the controller.

Recommended Future Work

This project developed three V2I safety applications and conducted engineering evaluations to verify and refine application performance. To take the outcome of this research to real-world deployment, a number of research efforts could be pursued in the future; two were identified in this project and are recommended for future work. All three V2I applications developed in this project require an accurate map (i.e., an intersection for RLVW, a work zone for RSZW/LC, or curve in the case of CSW). While the current project focused on using static map generation, in reality, safety applications could be dramatically affected by temporary changes in roadway configuration due to such things as a lane closure, road construction or traffic incidents. It would be beneficial to investigate the feasibility of automatically generating and updating dynamic maps, in near real-time, for transmitting in the DSRC message to vehicles. A second effort would address future large-scale real-world deployment by providing procedures and tools to verify completeness and correctness of transmitted messages from the infrastructure. Such tools would be beneficial to organizations tasked with undertaking future systems deployments. Generation of dynamic maps and verification of transmitted DSRC messages are necessary elements for developing and deploying effective and robust applications to assist drivers in a connected transportation environment.

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APPENDIX A. List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AERIS	Applications for the Environment: Real-time Information Synthesis
ARP	Antenna Reference Point
ASN	Abstract Syntax Notation One
BIM	Basic Information Message
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAMP	Crash Avoidance Metrics Partners
CAN	Controller Area Network
CICAS-V	Cooperative Intersection Collision Avoidance System - Violation (Project)
COG	Center of Gravity
ConOps	Concept of Operations
CSW	Curve Speed Warning
CV	Connected Vehicle
CVRIA	Connected Vehicle Reference Implementation Architecture
DENM	Decentralized Environmental Notification Message
DGPS	Differential Global Positioning System
DII	Driver-Infrastructure Interface
DOP	Dilution of Precision
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communications
DVI	Driver-Vehicle Interface
eGUI	Engineering Graphical User Interface
ESD	Environmental Sensor Data
ESS	Environmental Sensor Station

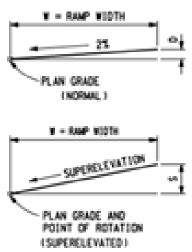
ETSI	European Telecommunications Standards Institute
EVPW	Emergency Vehicle Priority Warning
FDW	Flashing Don't Walk
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standards
FTTA	FT Techno of America
GAO	General Accountability Office
GID	Geometric Intersection Description
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
HMI	Human-Machine Interface
HV	Host Vehicle
I/O	Input / Output
I2V	Infrastructure-to-Vehicle
IDS	Infrastructure Data Systems
IEEE	IEEE (Formerly the Institute of Electrical and Electronics Engineers)
IOO	Infrastructure Owners and Operators
ITE	Institute of Transportation Engineers
ITIS	International Traveler Information System
ITS	Intelligent Transportation Systems
IVP	Integrated V2I Prototype
JPO	Joint Program Office
LC	Lane Closure
LIDAR	Light Detection and Ranging
m/s2	Meters per Second per Second (units for acceleration)
MAP	SAE J2735 Map Message

MDOT	Michigan Department of Transportation
MMITSS	Multi-Modal Intelligent Traffic Signal Systems
MUTCD	Manual on Uniform Traffic Control Devices
NEMA	National Electrical Manufacturers Association
NHTSA	National Highway Traffic Safety Administration
NPRM	Notice of Proposed Rulemaking
NTCIP	National Transportation Communications for ITS Protocol
OBE	Onboard Equipment
OBU	Onboard Unit
OEM	Original Equipment Manufacturer
OS	Operating System
OTA	Over-the-Air
OTP	Objective Test Procedure
PFS	Pooled Fund Study
RCOC	Road Commission for Oakland County (Michigan)
RLVW	Red Light Violation Warning
RS	Reduced Speed
RSE	Roadside Equipment
RSU	Roadside Unit
RSZW	Reduced Speed Zone Warning
RSZW/LC	Reduced Speed Zone Warning / Lane Closure
RSZW-RS/LC	Reduced Speed Zone Warning with Lane Closure and Reduced Speed Warning
RTCM	Radio Technical Commission for Maritime Services
RWIS	Road Weather Information System
SA	Safety Applications
SAE	SAE International
SAP	Safety Applications Processing (unit)

SEMI	South Eastern Michigan (Test Bed)
SPaT	Signal Phase and Timing
SR	Scenario Record
SSGA	Stop Sign Gap Assistance
SWIW	Spot Weather Impact Warning
SWIW-D	Spot Weather Impact Warning - Diversion
SWIW-RS	Spot Weather Impact Warning – Reduced Speed
TIM	Traveler Information Message
TMC	Traffic Management Center
TMT	Technical Management Team
TTI	Texas Transportation Institute
UDP	User Datagram Protocol
UMTRI	University of Michigan Transportation Research Institute
UPER	Unaligned Packed Encoding Rules
USB	Universal Serial Bus
USDOT	United States Department of Transportation
UTC	Coordinated Universal Time
V2I	Vehicle-to-Infrastructure
V2I-SA	Vehicle-to-Infrastructure Safety Applications (Project)
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Vehicle or Vehicle-to Infrastructure (generic)
VNC	Virtual Network Computing
WAVE	Wireless Access for Vehicular Environments
Wi-Fi	Wireless Fidelity (Wireless Local Network)
WSM	WAVE Short Message

APPENDIX B. Superelevation and Pavement Crowns

The information below was taken from the Michigan Department of Transportation (MDOT) Road and Bridge Standard Plans, Standard Plan Number R-107, Superelevation and Pavement Crowns. [18] The notations in red were prepared by the V2I-SA Project's Technical Management Team and indicate the radius of curvature and superelevation data relevant to the Curve Speed Warning application.



RAMPS

LEGEND

NC = NORMAL CROWN RATE

W = DISTANCE IN FEET FROM POINT OF ROTATION TO FARTHEST OUTSIDE EDGE

D = W × NC

e = RATE OF SUPERELEVATION

S = W × e

C = CROWN RUNOUT / TANGENT RUNOUT (ADVERSE CROWN REMOVED)

L = TRANSITION LENGTH OR SUPERELEVATION RUNOFF OF INSIDE OR OUTSIDE EDGE OF PAVEMENT

Δ% = SUPERELEVATION TRANSITION SLOPE OF PAVEMENT EDGES

Source – Road and Bridge standard plan (see section R-107)
http://mdotcf.state.mi.us/public/design/files/englishstandardplans/files/standard_plan_book.pdf

Since we may not have Posted advised speed Or speed limit, then Assume lowest speed

If R > 915 m Then e=0

When 915 m>= r > 426 m Then e= 2 deg

When 426 m >= r >182 m Then e= 3 deg

When 182 m >= r > 68 m Then e= 5 deg

When r =< 225 ft (68 m), then e=7 deg

OF SUPERELEVATION AND SUPERELEVATION TRANSITION SLOPE

RADIUS (FEET)	30 MPH		35 MPH		40 MPH		45 MPH		50 MPH		55 MPH		60 MPH		65 MPH		FREEWAYS				URBAN FREEWAYS AND URBAN RAMPS	
																	70 MPH		75 MPH		60 MPH	
	e %	Δ%	e %	Δ%	e %	Δ%	e %	Δ%	e %	Δ%	e %	Δ%	e %	Δ%	e %	Δ%	e %	Δ%	e %	Δ%	e %	Δ%
23000	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----
20000	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----
17000	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----
14000	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	2.0	0.31	2.0	0.30	NC	----
12000	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	2.0	0.32	2.0	0.31	2.0	0.30	NC	----
10000	NC	----	NC	----	NC	----	NC	----	NC	----	NC	----	2.0	0.36	2.0	0.32	2.1	0.31	2.3	0.31	2.0	0.34
8000	NC	----	NC	----	NC	----	NC	----	2.0	0.40	2.0	0.38	2.1	0.36	2.3	0.33	2.6	0.32	2.9	0.31	2.0	0.34
6000	NC	----	NC	----	NC	----	2.0	0.40	2.0	0.40	2.3	0.39	2.7	0.37	3.0	0.34	3.3	0.33	3.7	0.33	2.4	0.36
5000	NC	----	NC	----	2.0	0.40	2.0	0.40	2.3	0.41	2.7	0.39	3.1	0.38	3.5	0.35	3.9	0.34	4.4	0.34	2.8	0.37
4000	NC	----	2.0	0.45	2.0	0.40	2.4	0.41	2.8	0.42	3.3	0.40	3.8	0.39	4.2	0.37	4.7	0.36	5.3	0.35	3.3	0.39
3500	NC	----	2.0	0.45	2.2	0.41	2.6	0.42	3.1	0.42	3.6	0.41	4.2	0.40	4.7	0.38	5.2	0.37	5.9	0.36	3.5	0.40
3000	2.0	0.50	2.0	0.45	2.5	0.42	3.0	0.43	3.5	0.43	4.1	0.42	4.7	0.41	5.2	0.39	5.9	0.38	6.5	0.37	3.8	0.41
2500	2.0	0.50	2.4	0.46	2.9	0.43	3.5	0.44	4.1	0.44	4.7	0.43	5.3	0.42	5.9	0.41	6.5	0.39	7.0	0.38	4.2	0.42
2000	2.3	0.51	2.9	0.48	3.5	0.45	4.1	0.46	4.7	0.45	5.4	0.44	6.1	0.43	6.6	0.42	7.0	0.40	R MIN.= 2344'		4.6	0.44
1800	2.5	0.52	3.1	0.49	3.8	0.46	4.4	0.47	5.1	0.46	5.7	0.45	6.4	0.44	6.9	0.43	R MIN.= 1922'				4.8	0.44
1600	2.7	0.52	3.4	0.50	4.1	0.48	4.8	0.48	5.4	0.47	6.1	0.45	6.7	0.44	7.0	0.43					4.9	0.45
1400	3.0	0.53	3.7	0.51	4.5	0.49	5.1	0.49	5.8	0.48	6.5	0.46	6.9	0.45	R MIN.= 1565'						R MIN.= 1412'	
1200	3.4	0.54	4.1	0.52	4.9	0.50	5.6	0.50	6.3	0.49	6.8	0.47	R MIN.= 1263'									
1150	3.5	0.55	4.3	0.53	5.0	0.51	5.7	0.50	6.4	0.49	6.9	0.47										
1000	3.8	0.56	4.6	0.54	5.4	0.52	6.1	0.52	6.7	0.49	R MIN.= 1008'											
900	4.1	0.57	4.8	0.55	5.7	0.53	6.4	0.52	6.9	0.50												
820	4.3	0.57	5.1	0.55	5.9	0.54	6.6	0.53	7.0	0.50												
800	4.4	0.58	5.1	0.56	6.0	0.54	6.7	0.53	7.0	0.50												
720	4.6	0.58	5.4	0.57	6.3	0.55	6.9	0.54	R MIN.= 794'													
700	4.7	0.59	5.5	0.57	6.3	0.56	6.9	0.54														
600	5.0	0.60	5.9	0.58	6.7	0.57	R MIN.= 614'															
500	5.4	0.61	6.4	0.60	7.0	0.58																
450	5.7	0.62	6.6	0.61	R MIN.= 464'																	
400	6.0	0.63	6.8	0.61																		
350	6.3	0.64	7.0	0.62																		
300	6.7	0.65	R MIN.= 327'																			
265	6.9	0.66																				
225	7.0	0.66																				
	R MIN.= 222'																					

NOTES:

LOOP RAMPS SHALL HAVE A 7% RATE OF SUPERELEVATION.

THE RATE OF SUPERELEVATION FOR CURVES APPROACHING RAMP TERMINALS (STOPPING CONDITION) SHOULD BE LIMITED TO 5% MAX.

IF DELTA VALUES FROM THE CHART CANNOT BE OBTAINED FOR THE DESIGN RADIUS, USE THE MAXIMUM DELTA VALUE FOR THE CORRESPONDING SPEED.

FOR RADII LESS THAN THOSE TABULATED, (BUT NOT LESS THAN R MIN.), USE e_{max}. MAXIMUM SUPERELEVATION FOR URBAN FREEWAYS AND URBAN RAMPS (WITH A 60 MPH DESIGN SPEED) IS 5%. OTHERWISE e_{max} = 7% .

Source: Michigan Department of Transportation, Road and Bridge Standard Plans. Available: http://mdotcf.state.mi.us/public/design/files/englishstandardplans/files/standard_plan_book.pdf.

APPENDIX C. ASN.1 Structure for BIM

The following ASN.1 structure for the BIM is compatible with 201603 version of SAE J2735.

```
BIM DEFINITIONS AUTOMATIC TAGS::=

BEGIN

IMPORTS
DSRCmsgID, TemporaryID, DDateTime, DirectionOfUse, Position3D,
PositionalAccuracy, Heading, HeadingConfidence, SpeedLimitList,
LaneWidth, Speed, SpeedConfidence, PathHistory, RoadSegmentList,
ObstacleDistance, ConnectsToList, LaneID, NodeSetXY, DSRCmsgID, REG-
EXT-ID-AND-TYPE, RegionalExtension FROM DSRC {
};


BasicInformationMessage ::= SEQUENCE {
    commonContainer,
    mobileContainer      OPTIONAL,
    workzoneCont    WorkZoneContainer    OPTIONAL,
    curveContainer        OPTIONAL,

    -- Additional containers for regional testing can be added
       through this mechanism –

    regional SEQUENCE (SIZE(1..4)) OF
               RegionalExtension {{ REGION.Reg-BIMRegionalContainer
}} OPTIONAL,
    ...
}

-- Future containers for regional use are registered here --
REGION.Reg-BIMRegionalContainer DSRC.REG-EXT-ID-AND-TYPE ::= { ... }


ApproachLane ::= SEQUENCE {

    laneID LaneID OPTIONAL,
       -- The ID number assigned to this approach lane.
       -- This shall be unique compared to other geometry/approach
lanes IDs.
    approachClassification ApproachClassification,
       -- defines if the lane is leading to the event or not
       -- 0 - approach is definitely not leading to event
       -- 1 - approach is leading to the event with certainty
       -- 2 - approach might lead to the event
```

```
       -- 3 - only straight movement on the approach leads to the
event
       -- 4 - only left movement on the lane approach to the event
       -- 5 - only right movement on the lane approach to the event
       -- 6 - reserved1
       -- 7 - reserved2
    nodes NodeSetXY,
    connectsTo ConnectsToList OPTIONAL,
            -- a list of geometry/approach lanes that this approach
lane
            -- connects to.
     ...
}

CommonContainer ::= SEQUENCE {
     msgID           DSRCmsgID,
     stationID       TemporaryID          OPTIONAL,
     eventID         EventID,
     segmentedID     EventID              OPTIONAL,
     detTime         DDateTime            OPTIONAL,
     validityDur     ValidityDuration     OPTIONAL,
     causeCode       CauseCodeType,
     subCauseCode   ,
     refPos          Position3D,
     posAcc          PositionalAccuracy   OPTIONAL,
     heading         Heading              OPTIONAL,
     headingConf     HeadingConfidence    OPTIONAL,
     speedLimit      SpeedLimitList       OPTIONAL,
     traffDir        DirectionOfUse       OPTIONAL,
     width           LaneWidth            OPTIONAL,
      approach SEQUENCE (SIZE(1..10)) OF ApproachLane OPTIONAL,
     ... -- # LOCAL_CONTENT
}

MobileContainer ::= SEQUENCE {
     speed           Speed,
     speedConf       SpeedConfidence      OPTIONAL,
     path            PathHistory          OPTIONAL,
     ... -- # LOCAL_CONTENT
}

WorkZoneContainer ::= SEQUENCE {
     laneStatus            LaneStatus           OPTIONAL,
     laneClosOffsets       LaneClosOffsets      OPTIONAL,
     geometry              RoadSegmentList      OPTIONAL,
     length                Length               OPTIONAL,
     workersPresent        Activity             OPTIONAL,
```

```
    ... -- # LOCAL_CONTENT
}

LaneClosOffsets ::= SEQUENCE (SIZE(1..10)) OF ObstacleDistance

CurveContainer ::= SEQUENCE {
    frictCoeff              BIMCoefficientOfFriction OPTIONAL,
    advisorySpeed           Speed                    OPTIONAL,
    geometry                RoadSegmentList          OPTIONAL,
    surfaceCondition             OPTIONAL,
    material                RoadwayMaterial          OPTIONAL,
    radius                                 OPTIONAL,
    bankAng                 BankingAngle             OPTIONAL,
    obstacle                Activity                 OPTIONAL,
    reducedVis              Activity                 OPTIONAL,
    ... -- # LOCAL_CONTENT
}

BankingAngle ::= INTEGER (-63..64)
EventID ::= INTEGER (0..65535)
CauseCodeType ::= INTEGER {
    reserved (0),
    trafficCondition (1),
    accident (2),
    roadworks (3),
    adverseWeatherCondition-Adhesion (6),
    hazardousLocation-SurfaceCondition (9),
    hazardousLocation-ObstacleOnTheRoad (10),
    hazardousLocation-AnimalOnTheRoad (11),
    humanPresenceOnTheRoad (12),
    wrongWayDriving (14),
    rescueAndRecoveryWorkInProgress (15),
    adverseWeatherCondition-ExtremeWeatherCondition (17),
    adverseWeatherCondition-Visibility (18),
    adverseWeatherCondition-Precipitation (19),
    slowVehicle (26),
    dangerousEndOfQueue (27),
    vehicleBreakdown (91),
    postCrash (92),
    humanProblem (93),
    stationaryVehicle (94),
    emergencyVehicleApproaching (95),
    hazardousLocation-DangerousCurve (96),
    collisionRisk (97),
    signalViolation (98),
    dangerousSituation (99)
} (0..255)
```

```
SubCauseCode ::= INTEGER (0..255)
ValidityDuration ::= INTEGER (0..131072)
LaneStatus ::= INTEGER (0..2047)
Length ::= INTEGER (0..32767)
Activity ::= INTEGER (0..1)
BIMCoefficientOfFriction ::= INTEGER (0..127)
SurfaceCondition ::= ENUMERATED {
    dry         (0),
    moist       (1),
    wet         (2),
    flowing     (3),
    ice         (4),
    snow        (5),
    frost       (6),
    ...
}

RoadwayMaterial ::= ENUMERATED {
    asphalt          (0),
    concrete         (1),
    gravel           (2),
    ...
}

Radius ::= INTEGER (0..1023)

ApproachClassification ::= INTEGER(0..7)
END
```

APPENDIX D. Objective Tests for Red Light Violation Warning Application

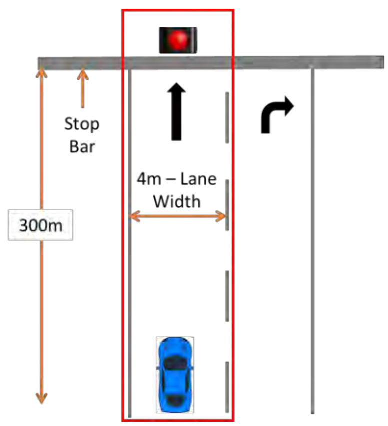
This appendix presents the details of the objective test procedures developed for the Red Light Violation Warning application.

D.1 Test 1: Reach Intersection on Red

In this test the HV is staged such that it reaches the intersection on a red signal phase.

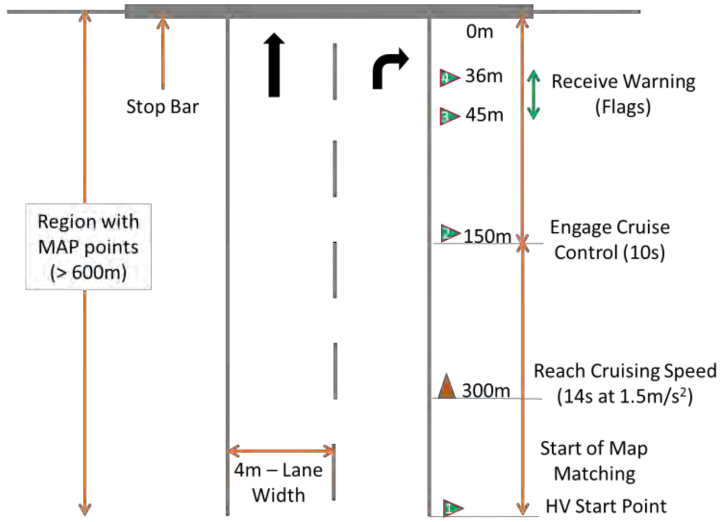
D.1.1 Test Goal

This test is intended to validate true positive Warning at an appropriate distance from the stop bar on a traffic lane with straight-only maneuver. In this test the signal phase is red as the HV approaches and reaches the stop bar. The test scenario is shown in Figure 123. The detailed layout geometry and flag placement for this test at 55 mph was shown previously in Figure 50 in Section 10.2.7. Similarly, the detailed layout geometry and flag placement for Test 1 at 35 mph and 70 mph are shown in Figure 124 and Figure 125, respectively.



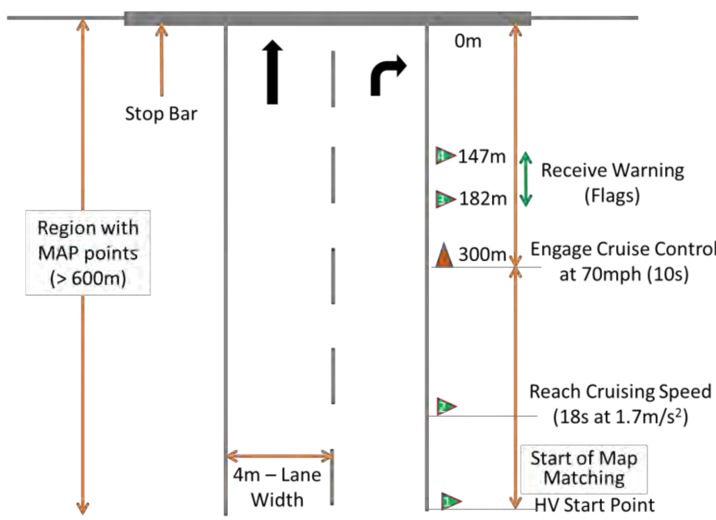
Source: CAMP – V2I Consortium

Figure 123: RLVW Test 1 Scenario



Source: CAMP – V2I Consortium

Figure 124: RLVW Test 1 Geometry – 35 mph Approach Speed



Source: CAMP – V2I Consortium

Figure 125: RLVW Test 1 Geometry – 70 mph Approach Speed

D.1.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1
- HV operator accelerates to reach target speed before reaching Flag 2
- HV operator maintains the target speed until receiving a Warning or until passing Flag 4

- If the HV operator receives the warning; unless mentioned otherwise, the operator brakes naturally when the Warning is generated until HV reaches to a full stop at or before the stop bar
- If the operator does NOT receive a Warning, the operator brakes naturally when the HV crosses Flag 4 and HV reaches a full stop
- Test run ends

D.1.3 Tests Conducted

This test is repeated for nine valid test runs for each test speed. Table 37 provides the list of test runs and the expected distance to Warning from the stop bar for Test 1.

Table 37: Test Runs Conducted for Test 1

Speed	Distance to Warning from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
70 (±2.5 mph)	147 m – 182 m	185 m – 229 m	9
55 (±2.5 mph)	90 m – 112 m	145 m – 177 m	9
35 (±2.5 mph)	36 m – 45 m	56 m – 73 m	9

Source: CAMP – V2I Consortium

D.1.4 Test Evaluation – Pass and Fail Criteria

A run was considered successful in this test if the warning was suppressed during the entire test run. The test was considered a “Pass” if at least 7 out of 9 valid test runs received a warning within the distance range specified in Table 37. Otherwise the test was considered a “Fail.”

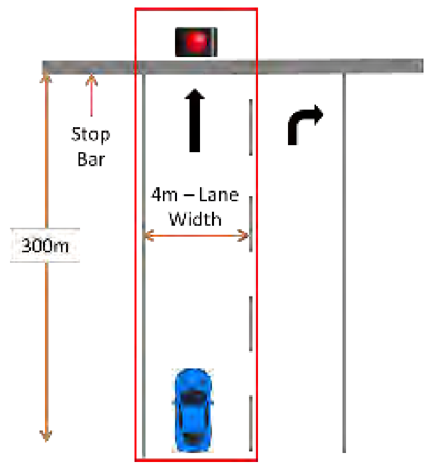
D.2 Test 2: Stop at the Intersection

In this test, the HV is staged such that it reaches the intersection while the signal phase is red as an indication for the driver to stop.

D.2.1 Test Goal

This test is intended to evaluate true negative Warning (meaning no Warning) where an HV will reach a full stop at the stop bar on a traffic lane permitting straight only maneuvers. In this test the signal phase is red as the HV reaches the stop bar.

The RLVW Test 2 geometry is described in Figure 126. The detailed geometry with flag placement for this test at 55 mph is shown in Figure 50 in Subsection 10.2.7.



Source: CAMP – V2I Consortium

Figure 126: RLVW Test 2 Scenario Geometry

D.2.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1
- HV accelerates to reach target speed before reaching Flag 2
- HV operator maintains target speed until reaching Flag 3
- HV operator applies brake (gently) at Flag 3 and keeps going with brake pressed
- Test run ends

D.2.3 Tests Conducted

This test was repeated for nine valid test runs for each test speed. Table 38 provides the list of test runs, and the expected distance to Warning from the stop bar for Test 2.

Table 38: Test Runs Conducted for Test 2

Speed	Distance to Warning from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
55 (±2.5 mph)	90 m – 112 m	113 m – 141 m	9
35 (±2.5 mph)	36 m – 45 m	45 m – 57 m	9

Source: CAMP – V2I Consortium

D.2.4 Test Evaluation – Pass and Fail Criteria

A run was considered successful if the warning is suppressed during the entire test run. The test was considered a “Pass” when 7 out of 9 valid test runs receive a warning within the warning distance range specified in Table 38. Otherwise the test was considered a “Fail.”

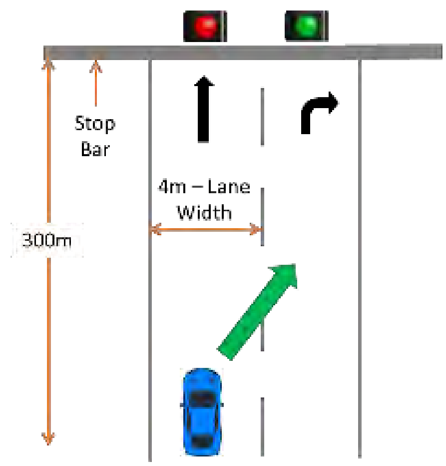
D.3 Test 3: Right Turn on Green

In this test the HV is staged such that it reaches the intersection on red for straight through movement, however it makes a lane change for right turn. The test is timed such that the right lane has green signal phase when the HV makes a lane change for warning suppression.

D.3.1 Test Goal

This test is intended to validate true negative Warning (meaning no warning) at an appropriate distance from the stop bar on a traffic lane with right only maneuvers. In this test, the signal phase is red on the through lane and green on the right turn lane as the HV approaches the intersection and turns right, as shown in Source: CAMP – V2I Consortium

Figure 127. The detailed geometry and flag placement for this test for 55 mph approach speed is shown in Figure 50 in Subsection 10.2.7.



Source: CAMP – V2I Consortium

Figure 127: RLVW Test 3 Scenario Geometry

D.3.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1
- HV operator accelerates to reach target speed before reaching Flag 2
- HV operator maneuvers to the right turn pocket (changes lanes to the right) between Flags 2 and 3
- HV operator makes a normal right turn, including deceleration and turn signal activation whenever it feels natural
- Test run ends

D.3.3 Tests Conducted

This test was conducted for nine valid test runs for each test speed. Table 39 provides the list of test runs, and the expected distance to Warning from the stop bar for Test 1.

Table 39: Test Runs Conducted for Test 3

Speed	Distance to Change Lane from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
55 (±2.5 mph)	90 m – 112 m	113 m – 141 m	9
35 (±2.5 mph)	36 m – 45 m	45 m – 57 m	9

Source: CAMP – V2I Consortium

D.3.4 Test Evaluation – Pass and Fail Criteria

A run is considered successful in this test if Warning is NOT provided to the driver at all. The test is considered a “Pass” when 7 out of 9 valid test runs are successful. Otherwise the test is considered a “Fail.”

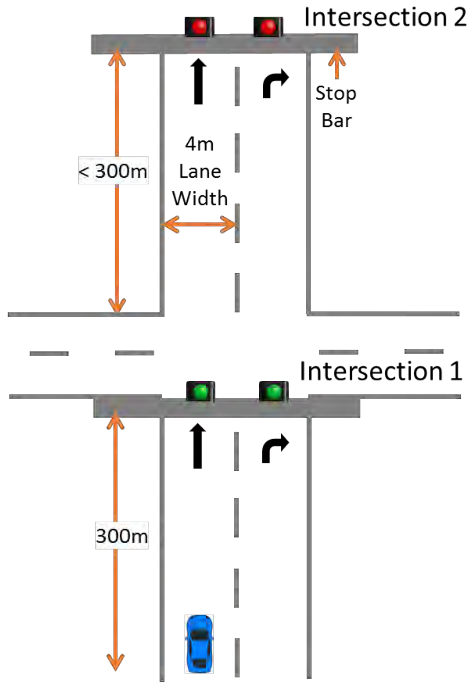
D.4 Test 4: Multiple Intersections within 300 m

This test considers a scenario where HV receives SPaT and MAP messages from multiple intersections and selects the most relevant intersection in the direction of travel.

D.4.1 Test Goal

This test is intended to validate the implementation of the relevance algorithm. The test involves two intersections as shown in Source: CAMP – V2I Consortium

Figure 128. The SPaT for the primary intersection (Intersection 1) is same as that in Tests 1 through 3. However, the signal phase for both lanes at the second intersection is always set to red. The map for two intersections is set such that the node points in the MAP message overlap. This enables the HV to be associated with two intersections at the start of the test. The goal of this test is to verify that as the HV approaches the first intersection, it selects SPaT messages from the most relevant intersection and provides the correct Inform / Warning message.



Source: CAMP – V2I Consortium

Figure 128: RLVW Test 4 Scenario Geometry

D.4.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1 such that

  - o HV arrives at intersection 1 on green phase for 9 runs
  - o HV arrives at Intersection 1 on red phase for 9 runs
- HV operator accelerates to reach target speed before reaching Flag 2
- HV operator maintains target speed until receiving a Warning or until passing Flag 4
- HV continues towards Intersection 2, and gets Warning between Flags 3 and 4 of Intersection 2
- HV operator brakes naturally when HV crosses Flag 4 and reaches full stop
- Test is repeated such that HV arrives at Intersection 1 on green phase

D.4.3 Tests Conducted

A total of nine test runs for each speed were conducted for this test. Table 40 provides the list of test runs, and the expected distance to Warning from the stop bar for Test 4.

Table 40: Test of Multiple Intersections within 300 m for Test 4

Speed (mph)	Distance to Warning from Stop Bar	Number of Runs
55 (±3.5 mph)	36 m – 45 m	9
35 (±2.5 mph)	90 m – 112 m	9

Source: CAMP – V2I Consortium

D.4.4 Test Evaluation – Pass and Fail Criteria

A run is considered successful for this test when following conditions are satisfied

- The HV receives 7 out of 9 Warnings at Intersections 1 and 2, when it reaches both intersections on red
- HV does not receive Warning at Intersection 1 when it reaches the intersection on green, but receives 7 out of 9 Warnings at Intersection 2

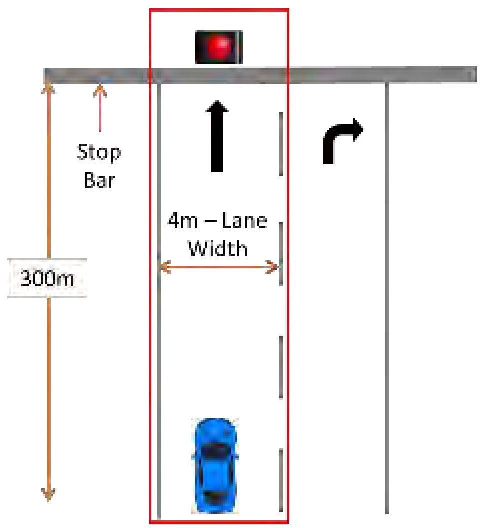
D.5 Test 5: Reach Intersection When Signal Turns Red

In this test the HV is staged such that it reaches the intersection when the signal phase has just turned red for generation of Warning.

D.5.1 Test Goal

This test is to validate that Warning will be generated when the signal phase changes to red just prior to the HV reaching to the stop bar. In this test the HV approaches the intersection while the signal phase is green. The test will be executed such that the signal phase changes to red just prior to the HV reaching to the stop bar. The test scenario is shown in Source: CAMP – V2I Consortium

Figure 129, and the relevant geometry with flag placement for this test is shown in Figure 50 in Subsection 10.2.7.



Source: CAMP – V2I Consortium

Figure 129: RLVW Test 5 Scenario Geometry

D.5.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1
- HV accelerates to reach target speed before reaching Flag 2
- HV operator maintains target speed until passing the stop bar
- HV operator brakes naturally after HV crosses the stop bar; HV reaches full stop
- Test run ends

D.5.3 Tests Conducted

This test was repeated for nine valid test runs for each test speed. Table 41 provides the list of test runs, and the expected distance to Warning from the stop bar for Test 5.

Table 41: Test Runs Conducted for Test 5

Speed	Distance to Warning from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
35 (±2.5 mph)	36 m – 45 m	46 m – 57 m	9
55 (±2.5 mph)	90 m – 112 m	113 m – 141 m	9

Source: CAMP – V2I Consortium

D.5.4 Test Evaluation – Pass and Fail Criteria

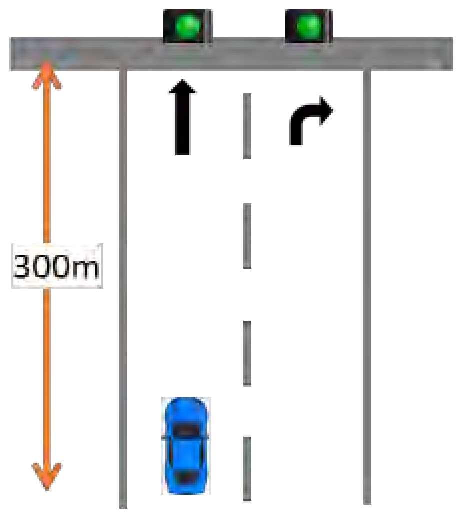
A run is considered successful in this test if Warning is suppressed during the entire test run. The test is considered a “Pass” when 7 out of 9 valid test runs received Warning within the warning distance range specified in Table 41. Otherwise the test is considered a “Fail.”

D.6 Test 6: Reach Intersection When Signal Turns Green

In this test the HV is staged such that it reaches the intersection when the signal phase has just turned green for warning suppression.

D.6.1 Test Goal

This test is intended to validate the suppression of the Warning message when the HV approaches the intersection at the start of the green phase. The test scenario is shown in Figure 130, and the relevant geometry with flag placement for the test is as shown in Figure 50 in Subsection 10.2.7.



Source: CAMP – V2I Consortium

Figure 130: RLVW Test 6 Scenario Geometry

D.6.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1, such that it would reach the intersection when the signal phase has just changed to green
- HV operator accelerates to reach target speed before reaching Flag 2
- HV does not receive any Warnings
- HV operator maintains target speed until passing the stop bar
- Test run ends

D.6.3 Tests Conducted

This test is repeated for nine valid test runs for each test speed. Table 42 provides the list of test runs and the expected distance to Warning from the stop bar for Test 6.

Table 42: Test Runs Conducted for Test 6

Speed	Distance to Warning from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
55 (±2.5 mph)	90 m – 112 m	113 m – 141 m	9

Source: CAMP – V2I Consortium

D.6.4 Test Evaluation – Pass and Fail Criteria

A run is considered successful in this test if the speed at which the vehicle crosses the intersection is constant without any Warning. The test is considered a “Pass” when 7 out of 9 valid test runs are successful. Otherwise the test is considered a “Fail.”

D.7 Test 7: Approach Lane Matching (Edge of Lane Testing)

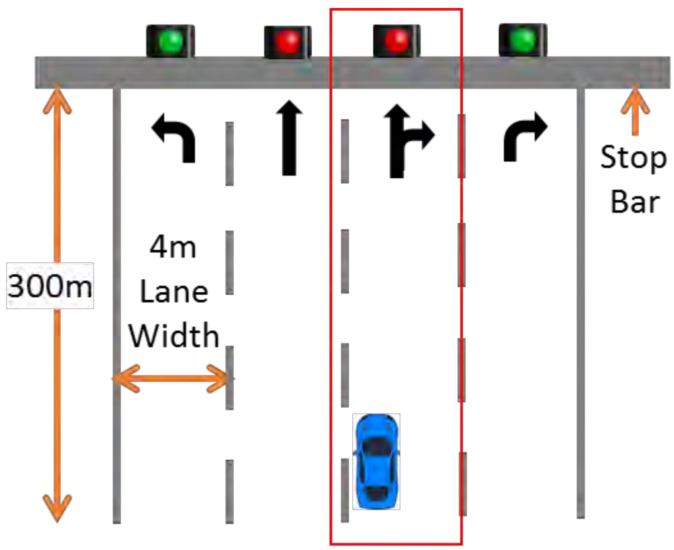
In this test the HV is staged such that it is driven on the edge of the lane and reaches the intersection on red for Warning generation after the lane matching is performed.

D.7.1 Test Goal

This test is intended to validate true positive Warning at an appropriate distance from the stop bar when the vehicle is driven on the edge of the lane. In this test the signal phase is red as the HV approaches and reaches the stop bar.

Source: CAMP – V2I Consortium

Figure 131 shows the RLVW Test 7 scenario, and the relevant geometry is shown in Figure 54 in Subsection 10.2.8.



Source: CAMP – V2I Consortium

Figure 131: RLVW Test 7 Scenario Geometry

D.7.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1
- HV accelerates to reach target speed before reaching Flag 2
- HV operator accelerates to reach target speed range and position the vehicle left tire ±0.25 m right from left lane marking by the time the vehicle reaches Flag 2
- HV operator maintains target speed until receiving a Warning or until passing Flag 4

- HV operator continues at the defined target speed until the vehicle passes the stop bar
- Test run ends
- Test is repeated such that the signal phase for the right turn lane is green when HV reaches the intersection
- HV operator turns the right turn indicator on before reaching Flag 3
- Turn prediction algorithm determines that HV intends to make a right turn, and HV does not receive a Warning since the operator intends to turn and the signal phase is green for right turn

D.7.3 Tests Conducted

This test is repeated for nine valid test runs for each test speed. Table 43 provides the list of test runs and the expected distance to Warning from the stop bar for Test 7.

Table 43: Test Runs Conducted for Test 7

Speed	Distance to Warning from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
35 (±2.5 mph)	36 m – 45 m	46 m – 57 m	9
55 (±2.5 mph)	90 m – 112 m	113 m – 141 m	9

Source: CAMP – V2I Consortium

D.7.4 Test Evaluation – Pass and Fail Criteria

A run is considered successful in this test if Warning is provided to the driver within an appropriate warning distance (between Flag 3 and Flag 4). The position of the HV relative to the lane edge must be ±0.25 m to the right of the left lane marking. The test is considered a “Pass” when 7 out of 9 valid test runs are successful. Otherwise the test is considered a “Fail.”

D.8 Test 8: Right Turn on Red

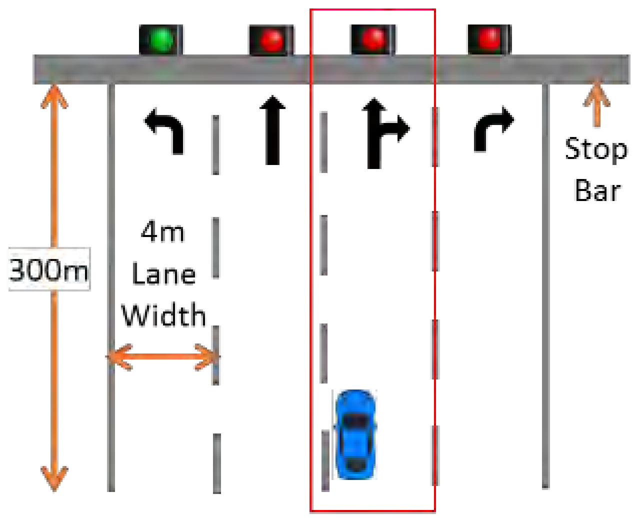
In this test the HV is staged on a lane with permitted through movement and right turn such that it reaches the intersection on red and decelerates before making a right turn on red for Warning suppression.

D.8.1 Test Goal

This test is intended to validate Warning suppression for right turn after stop at the stop bar on a traffic lane with straight and right turn maneuvers allowed. In this test, the signal phase is red as the HV approaches and reaches the stop bar.

Source: CAMP – V2I Consortium

Figure 132 shows scenario for the RLVW Test 8 and the detailed geometry and flag placement is shown in Figure 54 in Subsection 10.2.8.



Source: CAMP – V2I Consortium

Figure 132: RLVW Test 8 Scenario Geometry

D.8.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1
- HV operator accelerates to reach target speed before reaching Flag 2
- HV operator maintains target speed as long as he/she sees fit
- HV operator then performs a turn-on-red maneuver that feels natural considering the current selected speed

- Depending on the test run, the maneuver is performed including coming to a full stop at the stop bar, or slowing down to 5 mph, and continuing immediately with the turn maneuver
- Test run ends

D.8.3 Tests Conducted

This test is repeated for nine valid test runs for each test speed. Table 44 provides the list of test runs and expected distance to Warning from the stop bar for Test 8.

Table 44: Test Runs Conducted for Test 8

Speed	Distance to Warning from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
70 (±2.5 mph) w/ rolling stop	N/A	N/A	9
55 (±2.5 mph) w/ rolling stop	N/A	N/A	9
55 (±2.5 mph) w/ full stop	N/A	N/A	9

Source: CAMP – V2I Consortium

D.8.4 Test Evaluation – Pass and Fail Criteria

A run is considered successful in this test if no Warning is provided to the driver while turning right when performing a rolling stop or a full stop at the stop bar. The test is considered a “Pass” when 7 out of 9 valid test runs are successful. Otherwise the test is considered a “Fail.”

D.9 Test 9: Late Lane Change

In this test the HV is staged such that it reaches the intersection on red for a late lane change for right turn which is green for Warning suppression.

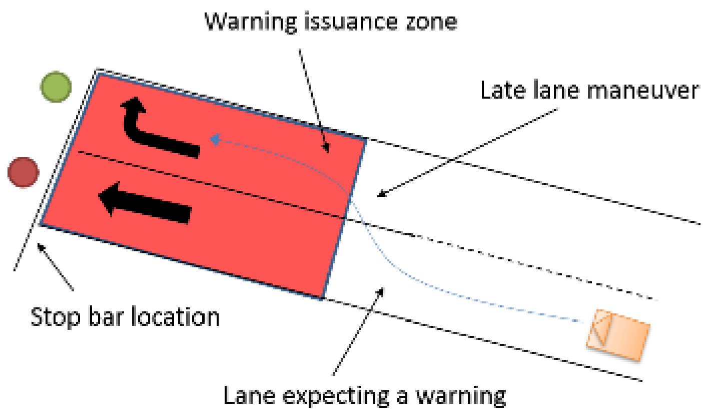
D.9.1 Test Goal

The main goal of this test is to validate that the RLVW system suppresses the Warning generation when the driver shifts from a lane which expects the Warning, to a lane which does not expect the Warning. This scenario is shown in Source: CAMP – V2I Consortium

Figure 133. The figure shows a vehicle approaching an intersection on a lane which has an active red phase. In a normal situation, the driver must be warned of a possibility of red light violation if it continues to traverse this lane on the same speed. However, the driver makes a late lane maneuver to the right lane, whereby the system should suppress any RLVW generation.

To test this condition, the HV will approach the intersection on the lane which expects the Warning, until the vehicle enters the warning zone (as shown in red in Figure 133). Inside that zone the vehicle will move to the right lane.

Figure 133 shows the RLVW Test 9 scenario, and the detailed geometry and flag placement is as shown in Figure 50 in Subsection 10.2.7.



Source: CAMP – V2I Consortium

Figure 133: RLVW Test 9 Late Lane Change Scenario

D.9.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1
- HV accelerates to reach target speed before reaching Flag 2
- HV operator maintains target speed until entering the warning zone
- HV operator starts lane change maneuver to come to the right-most lane at Flag 3
- HV reaches to a complete stop at the stop bar

- HV operator makes a normal right turn
- Test run ends

D.9.3 Tests Conducted

This test was repeated for nine valid test runs for each test speed. Table 45 provides the list of test runs for Test 9 – one of the two speeds was selected, depending on weather conditions. Repetitions with and without GPS corrections are required.

Table 45: Test Runs Conducted for Test 9

Speed	Distance to Change Lane from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
35 (±2.5 mph)	36 m – 45 m	44 m – 58 m	9
55 (±2.5 mph)	90 m – 112 m	113 m – 141 m	9

Source: CAMP – V2I Consortium

D.9.4 Test Evaluation – Pass and Fail Criteria

A run was considered successful in this test if no Warning is provided to the driver within an appropriate warning distance (between Flag 3 and Flag 4). The test was considered a “Pass” if at least 7 out of 9 valid test runs were successful. Otherwise the test was considered a “Fail.”

D.10 Test 10: Reach Intersection on Yellow

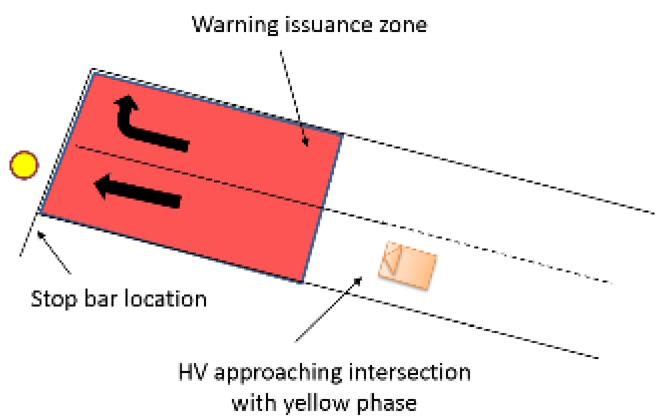
In this test the HV was staged such that it reaches the intersection on yellow for no Warning.

D.10.1 Test Goal

The main goal of this test is to validate that the RLVW system suppresses the Warning generation when the driver is approaching the intersection and the HV will cross the intersection while the signal phase will turn from green to yellow. Ideally the RLVW system should not issue a warning of red light violation to the driver based on the assumption that from the vehicle speed data, the algorithm will have a certain level of confidence that the driver will cross the intersection without encountering the red light.

To test this condition, the HV approached the intersection on the lane which expects the Warning, until the vehicle enters the warning zone (as shown in red in Figure 134). Once inside the zone, the operator will see the phase turning from green to yellow. The RLVW system should suppress the Warning if the HV has sufficient time to cross the intersection without facing a red light.

Figure 134 shows the RLVW test scenario. The detailed test geometry and flag placement is shown in Figure 50 in Subsection 10.2.7, highlighted in red. Figure 52 in Subsection 10.2.7 shows the SPaT plan used to conduct this test.



Source: CAMP – V2I Consortium

Figure 134: RLVW Test 10 Yellow Phase Approach Scenario

D.10.2 Test Script

- Test run begins
- HV takes off from full stop at Flag 1
- HV operator accelerates to reach target speed before reaching Flag 2
- HV operator maintains target speed until entering the warning zone

- The signal phase when HV crosses Flag 3 should be yellow
- HV operator maintains current speed and crosses the intersection
- HV operator brakes until the vehicle comes to a full stop
- Test run ends

D.10.3 Tests Conducted

This test is repeated for nine valid test runs for each test speed. Table 46 provides the list of test runs and expected distance to Warning from the stop bar for Test 10.

Table 46: Test Runs Conducted for Test 10

Speed	Distance to Warning from Stop Bar		Number of Runs
	Passenger Vehicles	Trucks	
55 (±2.5 mph)	90 m – 112 m	113 m – 141 m	9

Source: CAMP – V2I Consortium

D.10.4 Test Evaluation – Pass and Fail Criteria

A run is considered successful in this test if no Warning is provided to the driver. The test is considered a “Pass” when 7 out of 9 valid test runs are successful. Otherwise the test is considered a “Fail.”

D.11 Additional RLVW Tests – Test Facility at the University of Michigan

Following the tests conducted at FTTA test track and detailed test data analysis, the RLVW algorithm was further refined to incorporate the determination of the correct signal group for lanes that support multiple movements (e.g., straight and right turn) with appropriate signal phase. A single lane for example could be associated with two signal phases: 1) for a straight movement and 2) for a right turn movement. Additional test conditions and scenarios were defined and tests were conducted at the test facility at the University of Michigan. Figure 48 (a) and (b) in Section 10.1 previously showed the test facility and setup for testing the RLVW application. Software in the RSU and Onboard Unit (OBU) were updated as specified in the SAE J2735-1603 standard to:

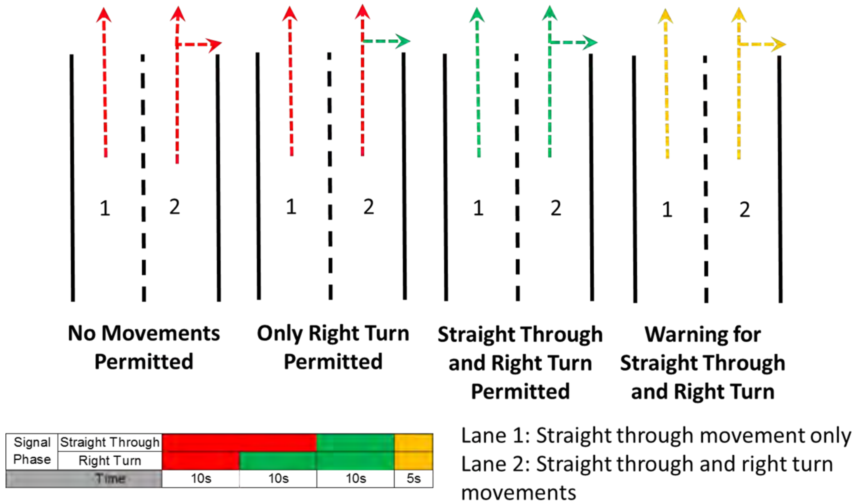
- Use the *maneuver* field in the MAP message to associate a lane for all permitted maneuvers
- Associate multiple signal groups as required by the lane

In addition, the application in the OBU was modified to select the anticipated movement of the vehicle based on the developed turn prediction algorithm which considers vehicle position, turn signal status and acceleration/deceleration.

Additional tests were also conducted to ensure compatibility of the updated software with the previous version:

- Association validation test for a lane with permitted multiple movements
    - Associate with through movement phase when HV’s turn signal indicator is not activated
    - Change associate to right turn movement phase when HV’s turn signal indicator is activated
- Only right turn permitted test
    - HV to reach the intersection when signal phase for through movement is red and right turn movement is green
    - Generate a Warning when HV’s right turn signal indicator not activated
    - Do not generate a Warning when HV’s right turn signal indicator is activated
    - Generate a Warning while HV’s right turn signal indicator is not activated; activate the right turn signal indicator to suppress the Warning
    - Generate a Warning when left turn signal indicator is activated

The SPaT setting for the tests is shown in Figure 135.

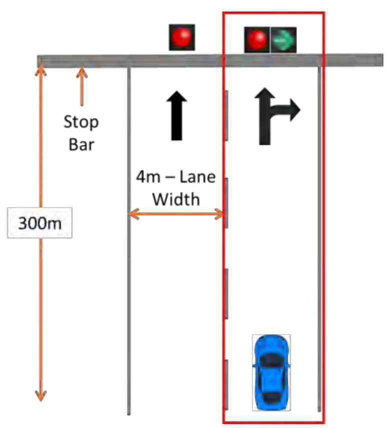


Source: CAMP – V2I Consortium

Figure 135: SPaT for Conducted Tests

D.11.1 Association Validation Test

This test is intended to validate appropriate association of the HV's lane with signal phase in the RLVW application. Test scenario geometry shown in Figure 136 is used for the following five test scenarios.



Source: CAMP – V2I Consortium

Figure 136: RLVW Tests Scenario Geometry

D.11.1.1 Test Script

- Test run begins
- HV takes off on the right lane from full stop at the start point
- HV operator accelerates to reach target speed

- HV operator toggles the right turn signal indicator on and off
- Test run ends when HV reaches the intersection

D.11.1.2 Tests Conducted

This test was performed in five CAMP test vehicles.

D.11.1.3 Test Evaluation – Pass and Fail Criteria

A run is considered successful if the RLVW algorithm:

- Associates HV's position with through movement phase when turn signal indicator is not activated
- Alters association to right turn movement phase when the right turn signal indicator is activated

It was observed that all test runs were successful.

D.11.2 Application Validation – Right Turn Signal Indicator OFF

This test is intended to validate proper association of lane with signal phase and performance of threat assessment by the application. In this test, a lane is associated with signal phases for through as well as right turn movements and the right turn signal indicator of the HV is not activated.

D.11.2.1 Test Script

- Test run begins
- HV takes off on the right lane from full stop at the start point such that it has to reach the intersection when the through movement has red phase and right turn movement has green phase
- HV operator accelerates to reach target speed
- HV operator maintains target speed
- Test run ends when HV reaches the intersection

D.11.2.2 Tests Conducted

This test was performed in five CAMP test vehicles.

D.11.2.3 Test Evaluation – Pass and Fail Criteria

A run is considered successful if the application generated a Warning. It was observed that all test runs were successful.

D.11.3 Application Validation – Right Turn Signal Indicator ON

This test is intended to validate proper association of lane with signal phase and performance of threat assessment by the application. In this test, a lane is associated with signal phases for through as well as right turn movements and the right turn signal indicator of the HV is activated.

D.11.3.1 Test Script

- Test run begins
- HV takes off on the right lane from full stop at the start point such that it has to reach the intersection when the through movement has red phase and right turn movement has green phase
- HV operator accelerates to reach target speed and activates the right turn signal indicator
- HV operator maintains the target speed
- Test run ends when HV reaches the intersection

D.11.3.2 Tests Conducted

This test was performed in five CAMP test vehicles.

D.11.3.3 Test Evaluation – Pass and Fail Criteria

A run is considered successful if the application does not generate a Warning. It was observed that all test runs were successful.

D.11.4 Application Validation – Warning Suppression

This test is intended to validate proper association of lane with signal phase and performance of threat assessment by the application. In this test, a lane is associated with signal phases for through as well as right turn movements. The right turn signal indicator of the HV is activated after the Warning is generated to indicate HV is turning right. The Warning is then suppressed.

D.11.4.1 Test Script

- Test run begins
- HV takes off on the right lane from full stop at the start point such that it has to reach the intersection when the through movement has red phase and right turn movement has green phase
- HV operator accelerates to reach target speed
- HV operator maintains target speed and activates the right turn signal indicator after receiving a Warning for through movement
- HV operator continues to drive towards the intersection with activated right turn signal indicator
- Test run ends when the HV reaches the intersection

D.11.4.2 Tests Conducted

This test was performed in five CAMP test vehicles.

D.11.4.3 Test Evaluation – Pass and Fail Criteria

A run is considered successful if the application turns off the generated Warning as soon as the right turn signal indicator is turned on.

It was observed that all test runs were successful.

D.11.5 Application Validation – Left Turn Signal Indicator On

This test is intended to validate proper association of lane with signal phase and performance of threat assessment by the application. In this test, a lane is associated with signal phases for through as well as right turn movements. The left turn signal indicator of the HV is activated.

D.11.5.1 Test Script

- Test run begins
- HV takes off on the right lane from full stop at the start point such that it has to reach the intersection when the through movement has red phase and right turn movement has green phase
- HV operator accelerates to reach target speed
- HV operator maintains the target speed and activates the left turn signal indicator after receiving a warning for through movement
- HV operator continues to drive towards the intersection with the left turn indicator on
- Test run ends when HV reaches the intersection

D.11.5.2 Tests Conducted

This test was performed in five project test vehicles.

D.11.5.3 Test Evaluation – Pass and Fail Criteria

A run is considered successful if the RLVW algorithm generates warning as the HV approaches the intersection. It was observed that all test runs were successful.

A run is considered successful if the application continues to generate warning after the left turn signal indicator is activated. It was observed that all test runs were successful.

APPENDIX E. Objective Test Procedures for Curve Speed Warning Application

The details of the objective test procedures developed for the Curve Speed Warning application are presented in this appendix.

E.1 Test 1: Inform and Warning Verification – Single Radius Curve, Dry Road

- Minimum radius of curvature from BIM (specified in the BIM)
- Normal asphalt road
- Road condition dry

E.1.1 Test Goal

The main goal of this test procedure is to validate the time and location of Inform and Warnings 1 and 2 upon approaching a curve where:

- HV is approaching a single curve with min Radius of 100 m, and the vehicle Approach Speed is above the calculated V_{max}
- The calculated Vmax is based on the following received from BIM
  - Minimum radius of curvature: 100 m
  - Superelevation: 5˚
  - Coefficient of friction (μ): 0.65
- Inform is generated based on the Approach Speed at a distance corresponding to 10 seconds from the start of the curve
- Warning 1 is generated at a distance corresponding to a “comfortable” deceleration rate of 2.4 m/s^2
- Warning 2 is generated at a distance corresponding to an “uncomfortable” or “harsh” deceleration rate of 4.6 m/s^2.
- Both Warnings 1 and 2 include an additional distance that corresponds to a 1.8 second driver reaction time and DVI latency
- Both Warnings 1 and 2 are generated after the Inform (because the vehicle is travelling at speed above the calculated V_{max})

HV will approach the curve at 55 mph (40 mph for truck). First an Inform will be generated indicating approach to the curve. HV will continue towards the curve at the Approach Speed which is higher than the V_{max} for the curve and Warning 1 and Warning 2 will be generated. Once on the curve, HV will reduce the speed below Vmax and complete the test run.

E.1.2 Test Setup

In addition to the test set up mentioned in Subsection 10.3.4, the following flags were placed on the road:

- Flag 1 to indicate the HV start point at which the HV takes off to reach the Approach Speed based on individual test plan
- Flag 2 to indicate when the HV should achieve test-indicated Approach Speed
- Flag 3 to indicate when the Inform should be generated along with two markers that indicate the “Inform Pass Zone” (set at distance corresponding to ± 1 sec before/after Flag 3)
- Flags 4 and 5 to indicate when Warning 1 and Warning 2 should be generated along with two markers that indicate the “Warning Pass Zone” (set at distance corresponding to -1 sec before Flag 4 and +1 sec after Flag 5)
- Flag 6 to indicate the beginning of the curve (distance from which Inform and Warnings are generated)
- Flag 7 to indicate the end of the curve

E.1.3 Test Script

- Test run begins
- HV takes off from full stop and accelerates to target speed before it reaches Flag 2
- The test observer will observe and record if the Inform message generation occurs within the “Inform Pass Zone”
- HV operator maintains target Approach Speed
- Test observer will observe and record if Warnings 1 and 2 message generation occur within the “Warning Pass Zone”
- HV maintains target speed until after Warning 2 is generated
- HV operator begins to decelerate and drives at a comfortable speed through the end of the curve
- Test run ends

E.1.4 Tests Conducted

This test is repeated for six valid iterations for each test speed. Table 47 provides the list of iterations for Test 1.

Table 47: Test Runs Conducted for Test 1

Vehicle Type	Approach Speed	Calculated V_{max}	Distance to Inform from Flag 6 (start of the curve)	Distance to Warning 1 from Flag 6 (start of the curve)	Distance to Warning 2 from Flag 6 (start of the curve)
Passenger Vehicles	55 (± 3) mph	51 mph	197 m (± 25 m)	62 m (± 25 m)	54 m (± 25 m)
Trucks	40 (± 3) mph	33 mph	143 m (± 18 m)	53 m (± 18 m)	43 m (± 18 m)

Source: CAMP – V2I Consortium

E.2 Test 2: Warning Suppression – Single Radius Curve, Dry Road

- Minimum radius of curvature from BIM (specified in the BIM)
- Normal asphalt road
- Road condition dry

E.2.1 Test Goal

The main goal of this test procedure is to validate the suppression of Warnings 1 and 2 where:

- HV is approaching a single curve with min Radius of 100 m, and the vehicle Approach Speed is below the calculated V_{max}
- The calculated V_{max} is based on the following received from BIM
  - Minimum radius of curvature: 100 m
  - Superelevation: 5˚
  - Coefficient of friction (µ): 0.65
- Inform is generated based on the Approach Speed at a distance corresponding to 10 seconds from the start of the curve
- Warnings 1 and 2 are suppressed after the Inform (because the vehicle is travelling at a speed below the calculated V_{max})

HV will approach the curve at 35 mph (20 mph for truck). First an Inform will be generated indicating approach to the curve. HV will continue towards the curve at the Approach Speed which is lower than the V_{max} for the curve and no Warnings will be generated. Once on the curve, the HV will continue through the curve at a comfortable speed.

E.2.2 Test Setup

In addition to the conditions specified in Subsection 10.3.4, the following flags were placed on the road. For this test, Flag 3 and related "Inform Pass Zone" markers were repositioned to correspond to the different Inform distance.

- Flag 1 to indicate the HV start point at which the HV takes off to reach the Approach Speed based on individual test plan
- Flag 2 to indicate when the HV should achieve test indicated Approach Speed
- Flag 3 to indicate when the Inform should be generated along with two markers that indicate the “Inform Pass Zone” (set at distance corresponding to ± 1 sec before/after Flag 3)
- Flags 4 and 5 to indicate when Warning 1 and Warning 2 should be generated along with two markers that indicate the “Warning Pass Zone” (set at distance corresponding to -1 sec before Flag 4 and +1 sec after Flag 5)
- Flag 6 to indicate the beginning of the curve (distance from which Inform is generated)
- Flag 7 to indicate end of the curve

E.2.3 Test Script

- Test run begins
- HV takes off from full stop and accelerates to the desired speed before it reaches Flag 2
- Test observer will observe and record if the Inform message generation occurs within the “Inform Pass Zone”
- HV operator maintains the target Approach Speed
- Test observer will observe and record if the Warnings 1 and 2 message generation are suppressed before, after or within the “Warning Pass Zone”
- HV operator maintains speed until passing Flag 6 (start of the curve)
- HV operator begins to decelerate and drives at a comfortable speed through the end of the curve
- Test run ends

E.2.4 Tests Conducted

This test is repeated for six valid iterations. Table 48 provides the list of iterations for Test 2.

Table 48: Test Runs Conducted for Test 2

Vehicle Type	Approach Speed	Calculated Vmax	Distance to Inform from Flag 6 (start of the curve)	Distance to Warning 1 from Flag 6 (start of the curve)	Distance to Warning 2 from Flag 6 (start of the curve)
Passenger Vehicles	35 (± 3) mph	51 mph	125 m (± 16 m)	None	None
Trucks	20 (± 3) mph	33 mph	72 m (± 9 m)	None	None

Source: CAMP – V2I Consortium

E.2.5 Test Evaluation – Pass and Fail Criteria

A run is considered successful in this test if:

- An Inform message generation occurs in the "Inform Pass Zone"
- Warnings 1 and 2 are suppressed before, after and within the "Warning Pass Zone"

The test is considered a "Pass" if at least 4 out of 6 valid iterations are successful. Otherwise the test is considered a "Fail."

E.3 Test 3: Inform and Warning Verification – Single Radius Curve, Icy Road

- Minimum radius of curvature from BIM (specified in the message)
- Road surface asphalt
- Road surface condition icy

E.3.1 Test Goal

The main goal of this test is to validate the time and location of the generation of Inform and Warnings upon approaching a curve where:

- The vehicle is approaching a single curve with min Radius of 100 m, and the vehicle Approach Speed is above the calculated V_{max}
- The calculated V_{max} is based on the following received from BIM
  - Minimum radius of curvature: 100 m
  - Superelevation: 5˚
  - Coefficient of friction (μ) to represent icy asphalt conditions: 0.15
- Inform is generated based on the Approach Speed at a distance corresponding to 10 seconds from the start of the curve
- Warning 1 is generated at a distance corresponding to a "comfortable" deceleration rate of 2.4 m/s^2
- Warning 2 is generated at a distance corresponding to an "uncomfortable" or "harsh" deceleration rate of 4.6 m/s^2.
- Both Warnings 1 and 2 include an additional distance that corresponds to a 1.8 second driver reaction time and DVI latency
- Both Warnings 1 and 2 are generated after the Inform (because the vehicle is travelling at speed above the calculated V_{max})

HV will approach the curve at 55 mph (35 mph for truck). First an Inform will be generated indicating approach to the curve. HV will continue towards the curve at the Approach Speed which is higher than the V_{max} for the icy road condition, and Warning 1 and Warning 2 will be generated. Once on the curve, HV will drive through the curve at comfortable speed.

E.3.2 Test Setup

In addition to the conditions specified in Subsection 10.3.4, the following flags were placed on the road. For this test, Flags 4 and 5 and related “Warning Pass Zone” markers were repositioned to correspond to the different Warning 1 and Warning 2 distances.

- Flag 1 to indicate the HV start point at which HV takes off to reach the Approach Speed based on individual test plan
- Flag 2 to indicate when HV should achieve test-indicated Approach Speed
- Flag 3 to indicate when the Inform should be generated along with two markers that indicate the “Inform Pass Zone” (set at distance corresponding to ± 1 sec before/after Flag 3)
- Flags 4 and 5 to indicate when Warning 1 and Warning 2 should be generated along with two markers that indicate the “Warning Pass Zone” (set at distance corresponding to -1 sec before Flag 4 and +1 sec after Flag 5)
- Flag 6 to indicate the beginning of the curve (distance from which Inform and Warnings are generated)
- Flag 7 to indicate the end of the curve

E.3.3 Test Script

- Test run begins
- HV takes off from full stop and accelerates to the target speed before it reaches Flag 2
- Test observer will observe and record if the Inform message generation occurs within the “Inform Pass Zone”
- HV operator maintains the target Approach Speed
- Test observer will observe and record if the Warnings 1 and 2 message generation occur within the “Warning Pass Zone”
- HV operator maintains speed until after Warning 2 is generated
- HV operator begins to decelerate and drives at a comfortable speed through the end of the curve
- Test run ends

E.3.4 Tests Conducted

This test is repeated for six valid iterations. Table 49 provides the list of iterations for Test 3.

Table 49: Test Runs Conducted for Test 3

Vehicle Type	Approach Speed	Calculated V_{max}	Distance to Inform from Flag 6 (start of the curve)	Distance to Warning 1 from Flag 6 (start of the curve)	Distance to Warning 2 from Flag 6 (start of the curve)
Passenger Vehicles	55 (± 3) mph	30 mph	197 m (± 25 m)	132 m (± 25 m)	90 m (± 25 m)
Trucks	35 (± 3) mph	27 mph	125 m (± 16 m)	49 m (± 16 m)	39 m (± 16 m)

Source: CAMP – V2I Consortium

E.4 Test 4: Inform and Warning Verification – Single Radius Curve, Reduced Visibility

- Minimum radius of curvature from BIM (specified in the message)
- Reduced visibility event

E.4.1 Test Goal

The main goal of this test is to validate the generation of Inform and Warnings where:

- The vehicle is approaching a single curve with min Radius of 100 m, and the vehicle Approach Speed is above the calculated V_{max}
- The V_{max} is based on a default value associated with a "Low Visibility" message received from the BIM
- Inform is generated based on the Approach Speed at a distance corresponding to 10 seconds from the start of the curve
- Warning 1 is generated at a distance corresponding to a "comfortable" deceleration rate of 2.4 m/s^2
- Warning 2 is generated at a distance corresponding to an "uncomfortable" or "harsh" deceleration rate of 4.6 m/s^2.
- Both Warnings 1 and 2 include an additional distance that corresponds to a 1.8 second driver reaction time and DVI latency
- Warnings 1 and 2 are generated after the Inform (because the vehicle is travelling at speed above the calculated Vmax)

HV will approach the curve at 55 mph (40 mph for truck). First an Inform will be generated indicating that the HV is approaching the curve. HV will continue towards the curve at the Approach Speed which is higher than the V_{max} for the reduced visibility condition and Warning 1 and Warning 2 will be generated.

E.4.2 Test Setup

In addition to the conditions specified in Subsection 10.3.4, the following flags were placed on the road. For this test, Flags 4 and 5 and related "Warning Pass Zone" markers were repositioned to correspond to the different Warning 1 and Warning 2 distances.

- Flag 1 to indicate the HV start point at which HV takes off to reach the Approach Speed based on individual test plan
- Flag 2 to indicate when HV should achieve test-indicated Approach Speed
- Flag 3 to indicate when the Inform should be generated along with two markers that indicate the "Inform Pass Zone" (set at distance corresponding to ± 1 sec before/after Flag 3)
- Flags 4 and 5 to indicate when Warning 1 and Warning 2 should be generated along with two markers that indicate the "Warning Pass Zone" (set at distance corresponding to -1 second before Flag 4 and +1 second after Flag 5)
- Flag 6 to indicate the beginning of the curve (distance from which Inform and Warnings are generated)
- Flag 7 to indicate the end of the curve

E.4.3 Test Script

- Test run begins
- HV takes off from full stop and accelerates to the target speed before it reaches Flag 2
- Test observer will observe and record if the Inform message generation occurs within the "Inform Pass Zone"
- HV operator maintains the target Approach Speed
- Test observer will observe and record if the Warnings 1 and 2 message generation occur within the "Warning Pass Zone"
- HV operator maintains speed until after Warning 2 is generated
- HV operator begins to decelerate and drives at a comfortable speed through the end of the curve
- Test run ends

E.4.4 Tests Conducted

This test is repeated for six valid iterations. Table 50 provides the list of iterations for Test 4.

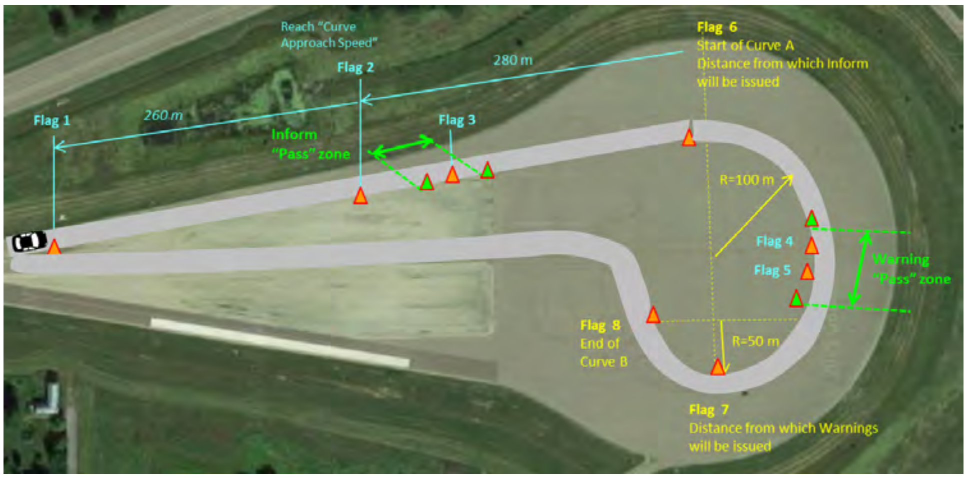
Table 50: Test Runs Conducted for Test 4

Vehicle Type	Approach Speed	Calculated Vmax	Distance to Inform from Flag 6 (start of the curve)	Distance to Warning 1 from Flag 6 (start of the curve)	Distance to Warning 2 from Flag 6 (start of the curve)
Passenger Vehicles	55 (± 3) mph	35 mph	197 m (± 25 m)	119 m (± 25 m)	83 m (± 25 m)
Trucks	40 (± 3) mph	35 mph	143 m (± 18 m)	48 m (± 18 m)	40 m (± 18 m)

Source: CAMP – V2I Consortium

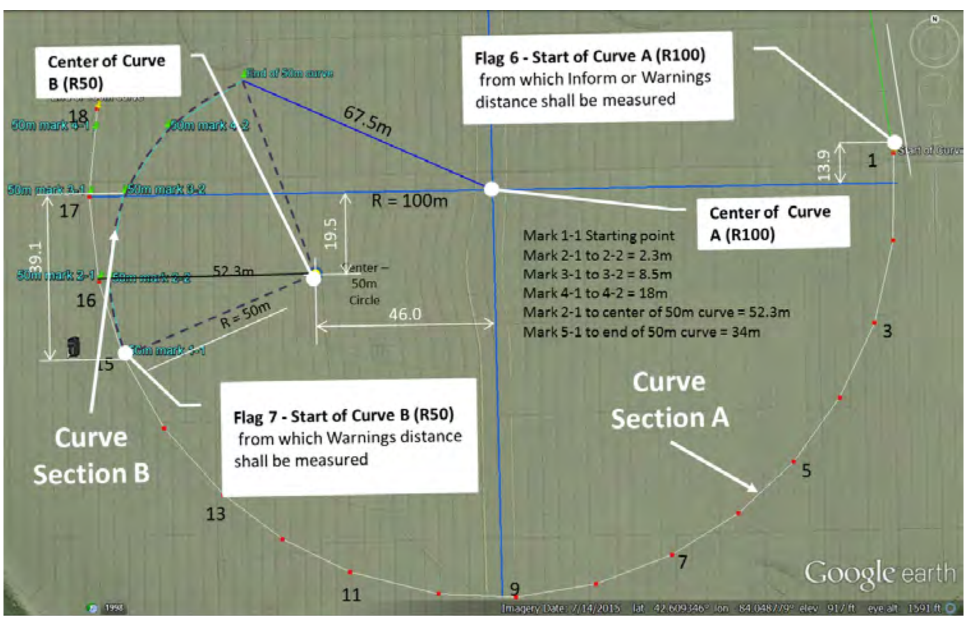
E.5 Tests 5 and 6 Setup and Layout – Multiple Radii Curve

Tests 5 and 6 involve a curve with varying radius. A single curve is defined by two radii curve sections A and B as shown in Figure 137. A larger-radius curve section of 100 m is followed by a smaller-radius curve section of 50 m. The transition from the first section to the second is abrupt to test algorithm performance. The Curve Section A contains 15 node points (map data points) and the curve section B contains four node points. Detailed geometry for the test curve is shown in Figure 138. The application used node segments for calculating segment-by-segment radius and V_{max} of each segment for generating warnings.



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 137: Setup and Layout for Tests 5 and 6



Source: Map image from Google. Used with permission. Plotted data from CAMP – V2I Consortium

Figure 138: Detailed Geometry for Tests 5 and 6

E.5.1 Test 5: Inform and Warning Verification – Multiple Radii Curve, Dry Road

- Multiple radii curves computed for each node segment from map data specified in the BIM
- Curve with multiple radii configuration
- Road surface: normal asphalt
- Road surface condition: dry

E.5.1.1 Test Goal

The main goal of this test is to validate the time and location of the generation of Inform and Warnings upon approaching a multiple radii curve where:

- HV is approaching two contiguous curves with
  - Curve Section A – a minimum Radius of 100 m
  - Curve Section B – a minimum Radius of 50 m
- HV Approach Speed is
  - Below the calculated Vmax for Curve Section A
  - Above the calculated V_{max} for Curve Section B
- The calculated Vmax is based on
  - Computed minimum radius for each node segment from map data
  - Superelevation: 5˚
  - Coefficient of friction (μ) for dry road: 0.65
- Inform is generated based on the Approach Speed at a distance corresponding to 10 seconds from the start of the Curve Section A
- Warning 1 is generated at a distance corresponding to a “comfortable” deceleration rate of 2.4 m/s^2
- Warning 2 is generated at a distance corresponding to an “uncomfortable” or “harsh” deceleration rate of 4.6 m/s^2
- Both Warnings 1 and 2 include additional distance corresponding to the Approach Speed in m/s x 1.8 seconds for driver reaction time and DVI latency
- Warnings 1 and 2 for Curve Section A will not be generated when Speed of HV is lower than the computed V_{max}
- Warnings 1 and 2 for Curve Section B will be generated when Speed of HV is higher than the computed Vmax

In this test, HV will approach the curve at 40 mph (same for Truck). First an Inform will be generated indicating approach to the curve. HV will continue towards the curve at the Approach Speed which is lower than the V_{max} for the first curve (R ≈ 100 m for each node segment), and Warning 1 and Warning

2 will not be generated. HV will continue to approach the second curve (radius transitions from R ≈ 60 m to R ≈ 50 m) at the same speed, which is higher than the V_{max}. Warning 1 and Warning 2 will be generated at a distance from the start of the pertinent node segment.

E.5.1.2 Test Setup

In addition to the conditions specified in Subsection 0, the following flags were placed on the road:

- Flag 1 to indicate the HV start point at which HV takes off to reach the Approach Speed based on individual test plan
- Flag 2 to indicate when HV should achieve Approach Speed
- Flag 3 to indicate when the Inform should be generated along with two markers that indicate the “Inform Pass Zone” (set at distance corresponding to ± 1 sec before/after Flag 3)
- Flags 4 and 5 to indicate when Warning 1 and Warning 2 (for Curve Section B) should be generated along with two markers that indicate the “Warning Pass Zone” (set at distance corresponding to -1 sec before Flag 4 and +1 sec after Flag 5)
- Flag 6 to indicate the beginning of Curve Section A (for reference)
- Flag 7 to indicate the location of min Radius of Curve Section B (for reference)
- Flag 8 to indicate the end of Curve Section B

E.5.1.3 Test Script

- Test run begins
- HV takes off from full stop and accelerates to the target speed before it reaches Flag 2
- Test observer will observe and record if the Inform message generation occurs within the “Inform Pass Zone”
- HV operator maintains the target Approach Speed through Curve Section A
- Test observer will observe and record if the Warning 1 and 2 message generation occur within the “Warning Pass Zone” before Curve Section B
- HV operator maintains speed until after Warning 2 is generated
- HV operator starts to decelerate and drives at a comfortable speed through the end of Curve Section B
- Test run ends

E.5.1.4 Tests Conducted

This test is repeated for six valid iterations. Table 51 provides the list of iterations for Test 5.

Table 51: Test Runs Conducted for Test 5

Vehicle Type	Approach Speed	Calculated Vmax (Curve Section A / Curve Section B)	Distance to Inform from Flag 6 (Start of the Curve Section A)	Distance to Warning 1 from Start of the Curve Section B	Distance to Warning 2 from Start of the Curve Section B
Passenger Vehicles	40 (± 3) mph	(51/36) mph	143 m (± 20 m)	45 m (± 20 m)	39 m (± 20 m)
Trucks	40 (± 3) mph	(51/36) mph	143 m (± 20 m)	45 m (± 20 m)	39 m (± 20 m)

Source: CAMP – V2I Consortium

E.5.1.5 Test Evaluation – Pass and Fail Criteria

A run is considered successful in this test if:

- An Inform message generation occurs in the “Inform Pass Zone”
- Warnings 1 and 2 are not generated for Curve Section A
- Warnings 1 and 2 for Curve Section B are generated in the “Warning Pass Zone”

The test is considered a “Pass” if at least 4 out of 6 valid iterations are successful. Otherwise the test is considered a “Fail.”

E.5.2 Test 6: Inform and Warning Verification – Multiple Radii Curve, Icy Road

- Multiple radii for curves computed for each node segment from MAP data specified in the BIM
- Curve with multiple radii configuration
- Road surface: normal asphalt
- Road surface condition: icy

E.5.2.1 Test Goal

The main goal of this test is to validate the time and location of the generation of Inform and Warnings upon approaching a multiple radii curve where:

- HV is approaching 2 adjacent curves with:
  - Curve Section A – a minimum Radius of 100 m
  - Curve Section B – a minimum Radius of 50 m
- HV Approach Speed is:
  - Above the calculated V_{max} for Curve Section A

  - Above the calculated V_{max} for Curve Section B
- The calculated V_{max} is based on:
  - Computed minimum radius for each node segment from map data
  - Superelevation: 5°
  - Coefficient of friction (μ) for icy road: 0.15
- Inform is generated based on the Approach Speed at a distance corresponding to 10 seconds from the start of the Curve Section A
- Warning 1 is generated at a distance corresponding to a “comfortable” deceleration rate of 2.4 m/s^2
- Warning 2 is generated at a distance corresponding to an “uncomfortable” or “harsh” deceleration rate of 4.6 m/s^2
- Both Warnings 1 and 2 include additional distance corresponding to the approach speed in m/s x 1.8 seconds for driver reaction time and DVI latency
- Warnings 1 and 2 for Curve Section A will be generated when Speed of HV is greater than the computed V_{max}
- Warnings 1 and 2 for Curve Section B will be generated when Speed of HV is greater than the computed V_{max}

In this test, HV will approach the curve at 40 mph (same for Truck). First an Inform will be generated indicating approach to the curve. HV will continue towards the curve at the Approach Speed which is greater than the V_{max} for the first curve (R ≈ 100 m for each segment) and Warning 1 and Warning 2 will be generated before entering the first curve. HV will continue to maintain the Approach Speed to the second curve (radius transitions from R ≈ 60 m to R ≈ 50 m) which is also higher than the V_{max} for node segments for Curve Section B. Once Warning 2 is generated, it will continue through all the node segments for Curve Section A and for Curve Section B until HV speed drops below the V_{max}.

E.5.2.2 Test Setup

In addition to the conditions specified in Subsection 0, the following flags were placed on the road:

- Flag 1 to indicate the HV start point at which HV takes off to reach the Approach Speed based on individual test plan
- Flag 2 to indicate when the HV should achieve Approach Speed
- Flag 3 to indicate when the Inform should be generated along with two markers that indicate the “Inform Pass Zone” (set at distance corresponding to ± 1 sec before/after Flag 3)
- Flags 4 and 5 to indicate when Warning 1 and Warning 2 (for Curve Section A) should be generated for icy road condition along with two markers that indicate the “Warning Pass Zone” (set at distance corresponding to -1 sec before Flag 4 and +1 sec after Flag 5)
- Flag 6 to indicate the beginning of Curve Section A (for reference)
- Flag 7 to indicate the location of min Radius of Curve Section B (for reference)

- Flag 8 to indicate the end of Curve Section B

E.5.2.3 Test Script

- Test run begins
- HV takes off from full stop and accelerates to the target speed before it reaches Flag 2
- Test observer will observe and record if the Inform message generation occurs within the "Inform Pass Zone"
- HV operator maintains the target Approach Speed through Curve Section A
- Test observer will observe and record if the Warning 1 and Warning 2 message generation occur within the "Warning Pass Zone" before Curve Section A
- HV operator maintains speed after Warning 2 is generated for Curve Section A until Curve Section B begins
- HV operator begins to decelerate and drives at a comfortable speed through the end of Curve Section B
- Test run ends

E.5.2.4 Tests Conducted

This test is repeated for six valid iterations. Table 52 provides the list of iterations for Test 3.

Table 52: Test Runs Conducted for Test 6

Vehicle Type	Approach Speed	Calculated Vmax (Curve Section A / Curve Section B)	Distance to Inform from Flag 6 (Start of the Curve)	Distance to Warning 1 from Flag 6 (Start of the Curve)	Distance to Warning 2 from Flag 6 (Start of the Curve)
Passenger Vehicles	40 (± 3) mph	(30/30) mph	143 m (± 20 m)	61 m (± 20 m)	47 m (± 20 m)
Trucks	40 (± 3) mph	(30/30) mph	143 m (± 20 m)	61 m (± 20 m)	47 m (± 20 m)

Source: CAMP – V2I Consortium

E.5.2.5 Test Evaluation – Pass and Fail Criteria

A run is considered successful in this test if

- An Inform message is generated in the "Inform Pass Zone"
- Warnings 1 and 2 are generated for Curve Section A
- Warnings 1 and 2 continue through Curve Section A and Curve Section B until HV slows down below V_{max} for Curve Section B

The test is considered a "Pass" if at least 4 out of 6 valid iterations are successful. Otherwise the test is considered a "Fail."

APPENDIX F. Objective Test Procedures for Reduced Speed Zone Warning / Lane Closure Application

The objective test procedures for the Reduced Speed Zone Warning / Lane Closure application are presented in this appendix.

F.1 Tests 1 and 6: Reduced Speed

- Test reduced speed in work zone when workers are not present
- Tests conducted at both 70 mph (Test 1) and 45 mph (Test 6) Approach Speeds
- Tests do not include lane closure

F.1.1 Test Goal

This test procedure is to validate the time and distance from start of the work zone for generation of Inform and Warning under the following conditions

- Posted speed limit in the work zone when workers are not present is set to 60 mph and 35 mph respectively for 70 mph and 45 mph tests
- Continue to maintain vehicle speed at or above 67 mph / 52 mph (posted work zone speed limit +7 mph hysteresis) to receive Warning

F.1.2 Test Setup

Test layouts previously described in Subsection 10.4.1 are used for this test scenario.

- HV starts on Lane #1 (Through Lane)
- HV attains 70 mph / 45 mph speed before reaching Flag 2
- HV continues to maintain the target Approach Speed or above in the work zone
- Test observer to observe and record Inform initiated between Flags 2 and 3 designated as Inform Zone
- Test observer to observe and record Warning initiated between Flags 4 and 5 designated as Warning Zone for RSZW Test
    - Warning will continue in the work zone for speed above 67 mph / 52 mph
    - Warning will be turned off in the work zone for speed below 64 mph (for speed limit 70 mph) / 49 mph (for speed limit 45 mph)
- Test observer will observe and record Warning until end of work zone

F.2 Tests 2 and 7: Reduced Speed When Workers Present

- Test of RSZW when workers are present
- Tests conducted at 70 mph (Test 2) and 45 mph (Test 7) Approach Speeds
- Tests do not include lane closure

F.2.1 Test Goal

This test procedure is to validate the time and distance from start of the work zone for generation of Inform and Warning under the following conditions:

- Posted speed limit in the work zone when workers are present is set to 45 mph and 25 mph respectively for 70 mph and 45 mph tests
- Continue to maintain vehicle speed at or above 52 mph / 32 mph (posted work zone speed limit +7 mph hysteresis) speed limits to receive Warning

F.2.2 Test Setup

Test layouts previously described in Subsection 10.4.1 are used for this test scenario.

- HV starts on Lane #1 (Through Lane)
- HV attains 70 mph / 45 mph speed before reaching Flag 2
- HV continues to maintain the target Approach Speed or above in the work zone
- Test observer to observe and record Inform initiated between Flags 2 and 3 designated as Inform Zone
- Test observer to observe and record Warning initiated between Flags 4 and 5 designated as Warning Zone for RSZW when workers present test
  - Warning will continue in the work zone for speed above 52 mph (for 70 mph speed limit) / 32 mph (for 45 mph speed limit)
  - Warning will be turned off in the work zone for speed below 49 mph (for 70 mph speed limit) / 29 mph (for 45 mph speed limit)
- Test observer will observe and record Warning until end of work zone

F.3 Tests 3 and 8: One Lane Closure

- Test of one lane closure in work zone
- Tests conducted at 70 mph and 45 mph Approach Speeds
- Tests do not include reduced speed test

F.3.1 Test Goal

The test procedure is to validate the time and distance for issuance of Lane Closure (LC) Inform and Warning from start of the work zone under the following conditions:

- The vehicle Approach Speed is 70 mph (Test 3) / 45 mph (Test 8) on the lane that is closing ahead
- The vehicle continues to drive on the lane closing ahead for Warning

F.3.2 Test Setup

Test layouts described in Subsection 10.4.1 are used for this test scenario.

- HV starts on Lane #3 (Closing Lane)
- HV attains 70 mph / 45 mph speed before reaching Flag 2
- HV continues to maintain the target Approach Speed on the Closing Lane
- Test observer to observe and record Inform initiated between Flags 2 and 3 designated as Inform Zone for RSZW / LC
- Test observer to observe and record Warning initiated between Flags 4 and 5 designated as Warning Zone for LC Warning
    - Warning will continue until the lane change
- Test observer to observe and record Warning suppression after the lane change

F.4 Tests 4 and 9: Two Lane Closures

- Test of two lane closures in work zone
- Test conducted at 70 mph (Test 4) and 45 mph (Test 9) Approach Speeds
- Test of turn signal indication for LC Warning suppression

F.4.1 Test Goal

The goal of the test is to validate lane-level map matching and time and distance for generation of Inform and Warning from start of lane closure for Lane #3 and Lane #2 in the work zone. Additionally, the goal is to test the LC Warning suppression by turn signal indication under the following conditions:

- HV Approach Speed is 70 mph / 45 mph on the Closing Lane ahead
- HV continues to drive on Lane #3 that is closing ahead for Warning

- HV operator uses turn signal indicator to suppress LC warning
- HV operator conducts lane change to Lane #2, for a second LC warning
- HV continues to drive on Lane # 2 until the initiation of the LC Warning

F.4.2 Test Setup

Test layouts described earlier in Subsection 10.4.5 are used for this test scenario.

- HV starts on Lane #3 (first Closing Lane)
- HV attains 70 mph / 45 mph speed before reaching Flag 2
- HV continues to maintain the Approach Speed on the lane that is closing ahead
- Test observer to observe and record Inform initiated between Flags 2 and 3 designated as Inform Zone for RSZW / LC
- Test observer to observe and record Warning initiated between Flags 4 and 5 designated as Warning Zone for LC warning
  - Warning will continue until either lane change occurs or turn signal indication is initiated
- Activate “turn signal” indicator for lane change
- Test observer to observe and record LC Warning suppression
- HV operator conducts lane change to Lane #2 (second closing lane)
- HV operator deactivates “turn signal” indicator
- Test observer to observe and record LC Warning initiated between Flags 6a and 6b for second lane change
- HV operator activates “turn signal” indicator
- Test observer to observe and record LC Warning suppression
- HV operator conducts lane change to Lane #1
- Test observer to observe and record LC Warning is stopped (on Through Lane)
- HV continues driving until end of the work zone

F.5 Tests 5 and 10: Lane Closures and Reduced Speed

16.1.1 Test Goal

The goal of this test is to combine all test scenarios previously described into one comprehensive scenario to test and record application performance for lane closures, lane change warning suppression and reduced speed warning in work zone when workers are present for proper Inform and Warning distances under following conditions:

- The vehicle Approach Speed is 70 mph / 45 mph on the closing lane ahead
- Test for two lane closures (Lane #2 and Lane #3)
- Use turn signal indicator to suppress LC Warnings
- Lane change to Through Lane (Lane #1), for testing RSZW Warning when workers are present

16.1.2 Test Setup

Test layouts described in Subsection 10.4.5 are used for this test scenario:

- HV starts on Lane #3 (first Closing Lane)
- HV operator attains 70 mph / 45 mph speed before reaching Flag 2
- HV operator continues to maintain the target Approach Speed on the lane closing ahead
- Test observer to observe and record RSZW / LC Inform initiated between Flags 2 and 3 designated as Inform Zone for work zone / lane closure
- Test observer to observe and record RSZW / LC Warning initiated between Flags 4 and 5 designated as Warning Zone for lane closure and/or reduced speed in work zone
    - LC Warning will continue until either lane change occurs or turn signal indication is initiated
    - RSZW Warning will continue in the work zone for speed above 52 mph (for 70 mph speed limit) / 32 mph (for 45 mph speed limit)
    - RSZW Warning will be turned off in the work zone for speed below 49 mph (for 70 mph speed limit) / 29 mph (for 45 mph speed limit)
- HV operator activates “turn signal” indicator for lane change
- Test observer to observe and record LC Warning suppression
- HV operator conducts lane change to Lane #2 (second Closing Lane)
- HV operator deactivates “turn signal” indicator
- Test observer to observe and record LC Warning initiated between Flags 6a and 6b for second lane change
- HV operator activates “turn signal” indicator
- Test observer to observe and record LC Warning suppression
- HV operator conducts lane change to Lane #1 (Through Lane)
- Test observer to observe and record LC Warning is stopped (on Through Lane)

- Test observer to observe and record RSZW Warning continues above 52 mph (for 70 mph speed limit) / 32 mph (for 45 mph speed limit) when workers are present in a work zone
- HV continues driving until end of the work zone

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