Intersection Decision Support Surveillance System:
Design, Performance and Initial Driver Behavior Quantization

Report \#3 in the Series: Developing Intersection Decision Support Solutions

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# Intersection Decision Support Surveillance System: Design, Performance and Initial Driver Behavior Quantization 

# Report \#3 in the Series: Developing Intersection Decision Support Solutions 

# Final Report 

Prepared by:<br>Lee Alexander<br>Pi-Ming Cheng<br>Max Donath<br>Alec Gorjestani<br>Arvind Menon<br>Craig Shankwitz<br>Department of Mechanical Engineering and the ITS Institute<br>University of Minnesota

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## Table of Contents

Executive Summary
The Minnesota Approach
System Performance Summary
Driver Behavior Summary
Chapter 1: Introduction ..... 1
Chapter 2: System Design and Functional Requirements ..... 4
2.1 IDS Design Premise ..... 4
2.2 Technical Approach ..... 4
2.2.1 Driving Behavior Characterization using Roadside Sensing ..... 5
2.2.2 Surveillance for IDS Deployment ..... 7
2.2.2.1 IDS System Requirements ..... 8
2.2.2.1.1 MUTCD compatibility ..... 8
2.2.2.1.2 Operational requirements ..... 9
2.2.2.1.2.1 All weather operation. ..... 9
2.2.2.1.2.2 Initial purchase and installation cost. ..... 9
2.2.2.1.2.3 Operations cost ..... 9
2.2.2.1.2.4 Maintenance requirements ..... 9
2.2.2.1.2.5 Reliability ..... 10
2.2.2.1.2.6 Modular design ..... 10
Chapter 3: Mainline Surveillance Subsystem ..... 11
3.1. Objective ..... 11
3.2. Mainline Surveillance System Requirements ..... 11
3.2.1 Coverage area ..... 11
3.2.2 Continuous tracking ..... 12
3.2.3 Accuracy ..... 12
3.2.4 Fault Detection/Fault Tolerance ..... 12
3.3. CONSTRAINTS ..... 13
3.3.1 Proximity to Highway ..... 13
3.3.2 Low Voltage ..... 13
3.3.3 Break Away ..... 13
3.3.4 Restriction in Median ..... 13
3.4. SYSTEM COMPONENTS ..... 13
3.4.1 Sensors ..... 14
3.4.2 As Built Mainline Surveillance System ..... 16
3.4.2.1 Architecture and data flow. ..... 16
3.4.2.1.1 Sensor Layout ..... 16
3.4.2.1.2 Sensor Mounting ..... 19
3.4.2.1.3 Communication ..... 19
3.4.2.1.3.1 Radar Sensor Station Hardware ..... 19
3.4.2.1.3.2 Main Controller Cabinet Hardware ..... 21
3.4.2.1.4 Processing ..... 24
3.4.2.1.4.1 Sensor Station Local Processing ..... 24
3.4.2.1.4.2 Central Processing ..... 26
3.4.2.1.4.3 Radar Behavior Effects associated with application of vehicle- based radar for intersection surveillance systems ..... 32
3.4.2.1.5 Implementation ..... 34
3.4.2.1.5.1 Sensor Aiming ..... 34
3.4.2.1.5.2 System Performance ..... 35
Chapter 4: Minor Road Surveillance Subsystem ..... 54
4.1 Objectives ..... 54
4.2 REQUIREMENTS ..... 54
4.2.1 Presence detection ..... 54
4.2.2 Vehicle classification capability ..... 54
4.2.3 Subsystem coverage ..... 54
4.2.4 Insensitivity to vehicle design variations ..... 55
4.2.5 Bias in errors ..... 55
4.3 CONSTRAINTS ..... 55
4.3.1 Proximity to Highway ..... 55
4.3.2 Low Voltage ..... 55
4.3.3 Break Away ..... 55
4.3.4 Restriction in Median ..... 55
4.4 System Components ..... 55
4.4.1Sensors ..... 56
4.4.1.1 Imaging/Cameras ..... 56
4.4.1.2 Radar Sensors ..... 56
4.4.1.3 Loop detectors ..... 57
4.4.1.4 Scanning Laser Sensors ..... 57
4.4.2 As Built Description of the Minor Road Surveillance System ..... 58
4.4.2.1 Architecture and data flow ..... 58
4.4.2.1.1 Sensor Layout ..... 58
4.4.2.1.2 Sensor Mounting ..... 59
4.4.2.1.3 Communication ..... 60
4.4.2.1.4 Processing ..... 63
4.4.2.1.4.1Local Processing at the Detection Sensor Station ..... 63
4.4.2.1.4.2 Local Processing at the Classification Sensor Station ..... 67
4.4.2.1.4.3 Central Processing ..... 68
4.4.2.2 Implementation ..... 73
4.4.2.2.1 Sensor Mounting ..... 73
4.4.2.2.2 System Performance ..... 74
4.4.2.2.2.1 Classification System Performance ..... 74
4.4.2.2.2.2 Minor Road Vehicle Tracking System Performance ..... 81
Chapter 5: Crossroads (Median) Surveillance Subsystem ..... 84
5.1 ObJectives ..... 84
5.2 REQUIREMENTS ..... 84
5.2.1 Coverage area ..... 84
5.2.2 Accuracy ..... 84
5.3 Constraints ..... 84
5.3.1 Proximity to Highway ..... 84
5.3.2 Low Voltage ..... 85
5.3.3 Break Away ..... 85
5.3.4 Restriction in Median ..... 85
5.4 System Components ..... 85
5.4.1 Sensors ..... 85
5.4.1.1 Laser scanners ..... 86
5.4.1.2 Visible light cameras. ..... 86
5.4.1.3 Infrared / Thermal Imaging cameras ..... 87
5.4.1.4 Loop Detectors ..... 90
5.4.1.5 Radar ..... 90
5.5 As Built Description of the Crossroad System ..... 90
5.5.1 Sensor Placement and Image Acquisition. ..... 90
5.5.2 Image Processing Techniques. ..... 93
5.5.2.1 Visible-light Camera Image Processing ..... 93
5.5.2.2 Infrared Camera Image Processing ..... 96
5.5.3 Calibration Procedure ..... 97
5.5.4 Experimental Validation ..... 100
Chapter 6:: Communication Systems ..... 102
6.1 Communication System Functional Requirements ..... 102
6.1.1 Bandwidth ..... 102
6.1.2 Commercial off-the-shelf ..... 102
6.1.3 Operating environment ..... 102
6.2 Description of Communication Systems ..... 103
6.2.1 Hardwired Communication System ..... 103
6.2.1.1 Digital Communication ..... 103
6.2.1.1.1 100 Mbit/s backbone ..... 103
6.2.1.1.2 Range requirements ..... 103
6.2.1.1.3 Time synchronization ..... 104
6.2.1.1.4 Mainline radar sensor data flow. ..... 104
6.2.1.1.5 Vehicle classification lidar and radar sensor data flow ..... 104
6.2.1.2 Analog Video Communication ..... 104
6.2.2 Wireless Communication System ..... 107
6.2.2.1 Digital Communication ..... 107
6.2.2.1.1 Range ..... 108
6.2.2.1.2 Bandwidth ..... 108
6.2.2.1.3 Mainline radar sensor data flow ..... 108
6.2.2.1.4 Vehicle classification lidar and radar sensor data flow ..... 108
6.2.2.2 Analog Video Communication ..... 109
Chapter 7: Computation System Hardware ..... 110
7.1 Radar Station Computation Hardware ..... 110
7.2 Lidar Station Computation Hardware ..... 110
7.3 Main Controller Cabinet Computation Hardware ..... 111
Chapter 8: Data Analysis ..... 113
8.1 Data Collection and Storage ..... 113
8.1.1 Method ..... 113
8.1.2 Data Flow and Structure ..... 114
8.1.3 Data Collection and Storage ..... 115
8.2 Data Processing ..... 117
8.2.1 Creation of Database Tables ..... 117
8.2.2 Queries ..... 119
8.2.2.1 Gap Statistics ..... 119
8.2.2.1.1 Definition of Gap ..... 119
8.2.2.1.2 Time of Day Effects ..... 120
8.2.2.1.3 Vehicle Maneuver Effects. ..... 121
8.2.2.1.4 Vehicle Classification Effects ..... 122
8.2.2.1.5 Effect of Waiting Time ..... 122
8.2.2.1.6 Weather Effects ..... 123
8.2.2.1.7 Identification of Near Misses/Collisions ..... 123
8.2.2.1.8 Specialized Queries. ..... 123
8.3 Data Analysis ..... 123
8.3.1 General accepted gap analysis ..... 123
8.3.2 Intersection Zone Analysis ..... 126
8.3.3 Gaps as a function of time of day ..... 129
8.3.4 Gaps for different vehicle maneuvers ..... 132
8.3.5 Gaps as a function of vehicle classification ..... 133
8.3.6 Waiting for a Gap ..... 135
8.3.7 Gaps as a function of weather conditions ..... 139
8.3.8 Small Accepted Gap Analysis ..... 144
Chapter 9: Conclusions ..... 146
References ..... 150
Appendix A. EVT-300 Radar Performance
Appendix B. Virginia Tech Transportation Institute Research on Point Sensors
Appendix C. Point Sensor Analysis: Case Study of Minnesota Test Intersection
Appendix D. Intersection Decision Support Design Guide
Appendix E. Prototype License Plate Reader System

## List of Tables

Table 1. Description of Trajectories of Interest for Thru-Stop Intersections. ..... 5
Table 2. Theoretical Mainline Lane Coverage up to intersection. ..... 18
Table 3. Mainline Lane Coverage beyond intersection. ..... 18
Table 4: Maneuver categories for US 52 and Goodhue County Road 9. ..... 121
Table 5: Vehicle classification groupings. ..... 122
Table 6: Gap statistics for all accepted gaps and gaps of less than 10 seconds. ..... 126
Table 7: Gap statistics for the four zones in Figure 80. ..... 127
Table 8: Gaps statistics based on time of day. ..... 130
Table 9: Gap statistics for each vehicle maneuver. ..... 133
Table 10: Gap statistics for each vehicle classification. ..... 134
Table 11: Accepted gap statistics cross referenced with time waiting at the stop bar zone. ..... 137
Table 12: Gap statistics for different times vehicles were located in the median. ..... 139
Table 13: Gap statistics for various visibility groupings. ..... 141
Table 14: Gap statistics for various precipitation rate groupings. ..... 143
Table 15: Statistics for small gaps compared with the total gap statistics, broken down by category. ..... 144
Table 16. Experimental results for a truck target. ..... A-9
Table 17. Experimental results for a sedan target ..... A-9
Table 18. Multi-point detection sensor requirements ..... B-3

## List of Figures

Figure 1. Trajectories of interest for rural thru-Stop intersections ..... 6
Figure 2. Radar Coverage along mainline at the Hwy52 intersection. ..... 17
Figure 3. The design tool used to test various sensor placement configurations. ..... 18
Figure 4. Radar mount antenna assembly. (Dimensions in inches.) ..... 19
Figure 5. Sensor Station Layout ..... 20
Figure 6. Radar Sensor Station Dataflow ..... 20
Figure 7. Main Controller Cabinet Hardware ..... 22
Figure 8. Mainline Communication Dataflow Diagram. ..... 23
Figure 9. Radar Sensor Station Dataflow, ..... 24
Figure 10. Coordinate Conversion - Sensor Coordinates to State-Plane Coordinates. ..... 25
Figure 11. Sensor Collector Process at the Main Controller (Mainline Sensors) ..... 26
Figure 12. Filtering and temporal alignment of sensor data. ..... 29
Figure 13. State Estimator Data Flow ..... 31
Figure 14. Checking the lane history before making a lane change. ..... 32
Figure 15. Compensation for "pull-in" effect. Gray arrow represents vehicle trajectory. ..... 33
Figure 16. Radar antenna mounted on flanged channel ..... 34
Figure 17. Three Retro-reflective sensors mounted on the same vertical plane ..... 36
Figure 18. Dataflow diagram for the vehicle detection rate experiment. ..... 37
Figure 19. View from the overhead camera. ..... 38
Figure 20. Search Zone around the laser beam hit point. ..... 39
Figure 21. Lateral masking - Green target masks violet target. ..... 39
Figure 22. Longitudinal masking ..... 40
Figure 23. Dataflow for the mainline probe-vehicle experiment ..... 41
Figure 24. Definition of errors that were measured for the probe vehicle tests ..... 42
Figure 25. Error plots - Sedan driven in a single lane ..... 44
Figure 26. Error plots - Truck driven in a single lane. ..... 45
Figure 27. Error plots - Sedan changing lanes ..... 46
Figure 28. Error plots - Truck changing lanes ..... 47
Figure 29. Speed error for the sedan ..... 49
Figure 30. Sedan driven in a single lane with one radar shut down. ..... 50
Figure 31. Motorcycle used to determine distance at which radar cross-section is lost in heavy truck cross-section. ..... 52
Figure 32. Results of motorcycle-heavy truck radar signature study. ..... 53
Figure 33. Sensor Coverage along minor road at the Hwy52 intersection. ..... 59
Figure 34. Lidar sensor mount assembly. ..... 60
Figure 35. Sensor Station Hardware. ..... 61
Figure 36. Minor Road Communication Dataflow Diagram. ..... 62
Figure 37. Detection Sensor Station Dataflow. ..... 63
Figure 38. Optimal Lidar Height. ..... 65
Figure 39. Non-Optimal Lidar Height. ..... 66
Figure 40. Detection Sensor Station Dataflow ..... 67
Figure 41. Vertically Placed Lidar to measure vehicle profile ..... 68
Figure 42. Sensor Collector Process at the Main Controller (Minor Road Sensors). ..... 69
Figure 43. Pre-Filtering and projection of sensor data. ..... 71
Figure 44. State Estimator Data Flow. ..... 72
Figure 45. Radar antenna and Lidar Sensor (Horizontal) mounted on flanged channel ..... 73
Figure 46. Lidar Sensor (Vertical) mounted on flanged channel ..... 74
Figure 47. Vehicle Classification Experiment Dataflow Diagram ..... 75
Figure 48. Vehicle Classification Experiment Components. ..... 75
Figure 49. Vehicle Classification Experiment Schematic ..... 76
Figure 50. Vehicle Classification Analysis by a human operator. ..... 77
Figure 51. Vehicle Height Histogram (122 Vehicles) ..... 78
Figure 52. Vehicle Length Histogram (122 Vehicles) ..... 79
Figure 53. Consolidated Histogram of Vehicle Height and Length (122 Vehicles) ..... 80
Figure 54. Minor Road Performance Experiment Dataflow ..... 81
Figure 55. Errors with a sedan - Straight through maneuver. ..... 82
Figure 56. Errors with a sedan - Right turn maneuver. ..... 83
Figure 57. Images from the three infrared cameras evaluated ..... 89
Figure 58. Sensor coverage along crossroads at the Hwy52 intersection ..... 91
Figure 59. Video Signal Dataflow. ..... 92
Figure 60. Infrared camera, visible light camera and the infrared illuminator mounted on the camera mast. ..... 92
Figure 61. Regions of interest defined at module startup. ..... 93
Figure 62. Thresholding Example ..... 94
Figure 63. Processing of images from a visible-light camera ..... 95
Figure 64. Effect of vehicle headlights during low-light conditions ..... 96
Figure 65. Processing steps for images from the infrared camera. ..... 98
Figure 66. Night performance comparison of the cameras. ..... 99
Figure 67. Crossroads Performance Experiment Dataflow ..... 100
Figure 68. Results from an experimental run with a sedan in the median ..... 101
Figure 69. Data flow for Radar sensor data using both hardwired and wireless channels. ..... 105
Figure 70. Data flow for Lidar sensor data using both hardwired and wireless 802.11a ..... 106
Figure 71. Analog Data Flow for vision-based, hardwired crossroads surveillance system. ..... 107
Figure 72. Wireless Data Flow for Wireless, vision-based crossroads surveillance system. ..... 109
Figure 73: Data flow diagram ..... 114
Figure 74: Data flow diagram for data collection system. ..... 116
Figure 75: Data flow diagram for data processing and analysis ..... 118
Figure 76: Region map of US Highway 52 and Goodhue Country Road 9 ..... 120
Figure 77: All accepted gaps between February 1 and February 22, 2005 ..... 124
Figure 78: All accepted gaps below 10 seconds. ..... 125
Figure 79: Map of Highway 52 intersection showing region and zone definitions ..... 126
Figure 80: Accepted gap histograms for the four zones in Figure 80 ..... 127
Figure 81: Vehicle counts every ten seconds for vehicles on US 52 within surveillance system region of detection ..... 129
Figure 82: Accepted gaps for morning rush, day time, evening rush and night time ..... 130
Figure 83: Average number of detected vehicles during a 24 hour period ..... 131
Figure 84: Histogram for straight, right and left turn maneuvers. ..... 132
Figure 85: Histogram of gaps for each vehicle classification. ..... 134
Figure 86: Distance traveled for difference acceleration rates ..... 135
Figure 87: Time vehicles waited for an acceptable gap at the stop signs (zone 1 and 2) ..... 136
Figure 88: Gaps by time waiting at the stop bars (zone 1 and 2). ..... 137
Figure 89: Time vehicles waited in median (zone 7 and 8) ..... 138
Figure 90: Gap histogram for different time spent in median (zone 7 and 8). ..... 139
Figure 91: Histogram of visibility measurement from RWIS station one mile north of intersection ..... 140
Figure 92: Accepted gaps for various visibility groupings. ..... 141
Figure 93: Histogram of precipitation rates. ..... 142
Figure 94: Accepted gaps for various precipitation rate groupings. ..... 143
Figure 95. The EVT-300 Radar unit mounted on a Vernier Turntable. ..... A-3
Figure 96. Determination of the Radar Yaw Angle (w.r.t North). ..... A-4
Figure 97. Wireless data flow ..... A-4
Figure 98. Signal Flow Diagram for the data-collection process ..... A-5
Figure 99. Data Synchronization. ..... A-5
Figure 100. Radar Geometries for a two-lane road ..... A-6
Figure 101. Lateral \& Longitudinal Position Errors ..... A-8
Figure 102. Sensor coverage at various sensor orientations (Truck at $72 \mathrm{~km} / \mathrm{hr}$ ) ..... A-11
Figure 103. Lane classification error at various sensor orientation angles ..... A-11
Figure 104. Speed Error at various sensor orientations for two different lanes ..... A-12
Figure 105. Percentage of drivers based on stop decision ..... B-1
Figure 106. Missed violators with single-point detection sensors and continuous detection sensors (Simulation results) ..... B-2
Figure 107. Diagram of mainline leading to crossroads at Minnesota Test Intersection. Analysis is performed for point sensors assumed to be placed at locations A-E above. ..... C-1
Figure 108. Histograms of trajectory estimation errors from intersection locations A, B, D, and E for vehicles not making turns onto the minor road. ..... C-2
Figure 109. Histograms of trajectory estimation errors from intersection locations $\mathrm{A}, \mathrm{B}, \mathrm{D}$, and E for vehicles making turns onto the minor road. ..... C-3
Figure 110. Instrumented intersection schematic showing the location of the minor road vehicle classification sensors, some of the mainline radar sensors and the eventual driver-intersection interface (DII) ..... D-2
Figure 111. Cabling schematic for southbound lane. ..... D-3
Figure 112. Cabling schematic for northbound lane. ..... D-3
Figure 113. Roadside radar installation. ..... D-4
Figure 114. Radar station details. ..... D-5
Figure 115. A simplified radar sensor mounting bracket ..... D-6
Figure 116. Radar sensor mounting bracket. ..... D-6
Figure 117. Roadside radar processor station. ..... D-7
Figure 118. Radar station computer box with circuit breaker box below ..... D-8
Figure 119. Radar station equipment connection schematic. ..... D-9
Figure 120. Typical circuit breaker and power splice boxes at radar and laser scanner stations ..... D-10
Figure 121. Vertical and horizontal roadside laser scanners. ..... D-11
Figure 122. Laser scanner mount ..... D-12
Figure 123. Camera equipment cabinet schematic and parts list ..... D-13
Figure 124. Typical laser sensor station layout ..... D-14
Figure 125. Lowerable camera pole ..... D-15
Figure 126. Camera enclosures and mounts. Pole has been lowered for access to cameras ..... D-16
Figure 127. Camera electrical cabinet and base. ..... D-17
Figure 128. Camera equipment cabinet schematic. ..... D-18
Figure 129. Typical camera pole installation. ..... D-19
Figure 130. Main computer cabinet ..... D-20
Figure 131. Main computer cabinet and schematic ..... D-21
Figure 132. Main electrical power cabinet. ..... D-23
Figure 133. Inside of main electrical cabinet ..... D-24
Figure 134. Power cabinet wiring diagram ..... D-24
Figure 135. Prototype license plate reader system at Minnesota test intersection. ..... E-3
Figure 136. Typical image captured by license plate camera during daylight hours at the Minnesota test intersection. ..... E-5
Figure 137. Typical twilight exposure, occurring approximately $2 / 3$ of the exposures. .E-5
Figure 138. Not-so typical twilight exposure at the intersection ..... E-6
Figure 139. Typical nighttime exposure occurring in approximately 75\% of exposures ..... E-6
Figure 140. An atypical nighttime exposure at the Minnesota test intersection. ..... E-7

## Executive Summary

More than $30 \%$ of all vehicle crashes in the US occur at intersections; these crashes result in nearly 9000 annual fatalities, or approximately $25 \%$ of all traffic fatalities. Moreover, these crashes lead to approximately 1.5 M injuries/year, accounting for approximately $50 \%$ of all traffic injuries.

To address the intersection crash problem, the FHWA sponsored Infrastructure Consortium, consisting of state Department of Transportations (DOTs) and Universities from Minnesota, Virginia, and California, created the Intersection Decision Support (IDS) project, which was formed and given the task of developing technologies and approaches to mitigate the intersection crash problem. Three different problems are addressed as part of this initiative. Virginia is addressing signalized and stop controlled intersection violations and crashes. California is addressing Left Turn Across Path/Opposite Direction (LTAP/OD) violations, primarily in the urban and suburban setting. Minnesota has elected to address crashes at rural thru-Stop intersections.

In rural Minnesota, approximately one-third of all crashes occur at intersections. AASHTO recognized the significance of rural intersection crashes in its 1998 Strategic Highway Safety Plan, and identified the development and use of new technologies as a key initiative to address the problem of intersection crashes.

To clearly define the rural intersection crash problem, an extensive review of both the Minnesota Crash Database and research reports quantifying the national problem was undertaken; the results are documented in [1]. This study of 3,700 Minnesota intersections shows that crashes at rural expressway thru-STOP intersections have similar crash and severity rates when compared to all rural thru-STOP intersections. However, right angle crashes (which are most often related to gap selection) were observed to account for 36 percent of all crashes at the rural expressway intersections. At intersections that have higher than expected crash rates, approximately 50 percent of the crashes are right angle crashes (This $50 \%$ figure is up from the $28 \%$ for all rural thruSTOP intersections). Further investigation also found that drivers’ inability to recognize the intersection, and consequently run the STOP sign, was cause for only a small fraction of right angle crashes, whereas gap selection was the predominate problem. This is consistent with other findings; Chovan et al. [2] found that the primary causal factors for drivers who stopped before entering the intersection were:

1. The driver looked but did not see the other vehicle (62.1 \%)
2. The driver misjudged the gap size or velocity of the approaching vehicles (19.6 \%),
3. The driver had an obstructed view (14.0 \%), or
4. The roads were ice-covered (4.4 \%).

Of these four driver errors, the first three can be described as either problems with gap detection or gap selection.

The rural Intersection Decision Support (IDS) system should provide a driver with assistance in selecting and identifying an appropriate gap.

## The Minnesota Approach

The Minnesota Rural IDS system is designed to provide a driver the information needed to make correct decisions regarding the available gap. The system is designed to provide the safety benefits of a signalized intersection (fewer crashes, opportunities for all drivers to enter/cross the traffic stream, etc.) while minimizing the downsides (expense of installation, disruption of traffic flow, etc.). It should be noted, however, that the IDS system will not provide additional opportunities for drivers to enter/cross the traffic stream because unlike a traffic signal, it will not create gaps that were not already there.

The IDS system consists of four distinct components: sensors, computer processors, a communication subsystem and a driver interface. The sensors, computer processors, and the communication subsystem are used to determine the "state" of the intersection; a driver interface conveys timely, appropriate information to the driver waiting on the minor road. Sensors, processors and communication systems are addressed herein; the driver interface is dealt within Creaser, et al [3]

Mainline state information includes the location, speed, acceleration, and lane of travel of each vehicle within the surveillance zone. The state information combined with known intersection geometry facilitates the real time tracking of traffic gaps on the mainline. Minor road state information includes the position and speed of the vehicle on the minor road, and an estimate of the classification of the vehicle. Present classification separates vehicles into four categories: Motorcycle/passenger cars, SUV/light truck, medium duty truck/school bus, and heavy-duty truck/semi/motor coach/farm equipment

A central processor computes the "state" of the intersection at 10 Hz . Should an unsafe condition be detected by the threat assessment algorithm, the central processor initiates the proper warning to the driver through an infrastructure-based interface known as the Driver-Infrastructure Interface, or DII (For this phase of the project, a DII is not located at the test intersection. It will be installed and tested in a subsequent phase of the project). The system has been designed as an infrastructure based system, but will support cooperative systems as well. Figure 1 below illustrates the concept.

A prototype rural IDS system has been designed and built at the intersection of US 52 and County State Aid Highway 9 in Goodhue County, MN. This system has been designed for two purposes; first, to characterize driver behavior in terms of gaps selected by drivers under various traffic, weather, vehicle, and seasonal conditions. Understanding driver behavior in these conditions is critical to the development of a Driver-Infrastructure Interface that will provide a driver the needed information at the proper time. Preliminary data has shown that most drivers select gaps less than those recommended by AASHTO; the actual mean selected gap is on the order of 6 seconds.


Figure: Layout of Rural IDS System.

This information is critical if an effective, safe driver interface is to be deployed. Second, the intersection will serve as the initial deployment location for initial testing of the IDS system, including the driver interface. This rich data set collected by this intersection will enable a comprehensive "before" and "after" analysis so that the benefits of the system can be clearly demonstrated and quantified.

## Sensor components and design

Four sensor groups are used in this IDS system. The first group of sensors is based on radar, and is located along the mainline of the intersection. Radar, in general, provides the optimal solution in terms of tracking ability (including lane assignment), coverage area, range, accuracy, angular resolution, and cost.

The second sensor group provides information needed to classify vehicles (and possibly drivers) on the minor roads. Vehicle classification is required because of the variation of the dynamic capability of highway vehicles entering the intersection from the minor road.

The third sensor group provides information needed to measure the trajectories of vehicle in the crossroads (or median) of the intersection. The primary questions to be answered by collecting this data are whether drivers consistently stop in the median area to make a second gap decision, and whether gap selection behavior is different for vehicles waiting in the crossroads.

The fourth sensor group measures other factors that may influence the conditions or rate at which the traffic stream is entered or crossed. For instance, a comprehensive road/weather condition sensor would provide an indication of visibility and tire-road friction characteristics. This information can be correlated with gap acceptance data to better define gap warnings and advisories.

## Communication systems

At the present time, both hardwired and wireless communication is supported. A DSL modem is used to ensure reliable, 16.7 Mbps hardwired communications over the long distance between the radar stations and the main controller cabinet. In addition to wired communication, each sensor station is equipped with an 802.11 b wireless transceiver. Wireless communication is included so that cost:benefits of both hardwired and wireless systems can be validated as a means to establish an optimal deployment path.

## Computation Systems

A number of algorithms are used in the rural IDS system. The first of note are the radar processing algorithms. These algorithms transform target information from the radar coordinate frame to the frame, and filter out false targets by comparing target location to the local landscape using an on-board geospatial database. The geospatial database is a high accuracy (decimeter level) georeferenced system that provides all feature and attribute information in real time to the embedded computing system in a format that is
significantly different than the digital map used for navigation. Some might call it an enhanced digital map, but its architecture is intentionally different.

Analogous to the radar processing algorithms are the vehicle classification algorithms, which use laser scanner (lidar) information to assign a vehicle a classification category based on the side profile of the vehicle. This information is then sent to the central processor.

An estimator-based vehicle tracker assigns each vehicle entering the intersection a unique ID, and determines location, speed, and lane of travel as long as the vehicle remains within the intersection (a $1220 \mathrm{~m}(4002 \mathrm{ft}) \times 244 \mathrm{~m}(800 \mathrm{ft})$ area). Gap tracking uses the vehicle tracking results and known intersection geometry to determine the location, length, and speed of the available gaps. Gap data will be used to trigger the driver interface.

## System Performance Summary

In the following, the performance of the rural IDS system as of 16 February 2005 is provided. It should be noted that the system is overbuilt, and designed to be a reference system. Subsystems can be degraded in the future to support benefit:cost studies. Definition of limits of acceptable performance will derive the overall system performance specifications necessary to finalize a deployable system design.

Table: Mainline radar-based surveillance system performance summary.

| Measure | Value | Method used to test system |
| :--- | :--- | :--- |
| Detection rate | $>$ <br> $99.99 \%$ | Multiple sensor observations over 5 days, one missed <br> target |
| Location accuracy | $<$ <br> meters | High speed tests with DGPS equipped probe vehicle as <br> reference |
| Speed accuracy | 1.6 kph | High speed tests with DGPS equipped probe vehicle as <br> reference |
| Lane assignment <br> accuracy | $95 \%$ | High speed tests with DGPS equipped probe vehicle as <br> reference. (Ambiguity arises from lane change events.) |

Table below summarizes the performance accuracy of the lidar-based vehicle classification system. A misclassification error of one-category is defined as the misclassification of a vehicle category that is one category adjacent to the correct one. For example, if classes A, B, C, D, and E are available, a "B" class vehicle identified as a
"C" class is a one-category error; "B" class identified as a "D" class represents a twocategory error.

Table: Minor road lidar-based vehicle classification performance summary.

| Measure | Value | Method |
| :--- | :--- | :--- |
| Detection rate | $>99 \%$ | Human observation, no missed vehicles detected |
| Misclassification <br> rate | $<5 \%$ | Errors of one classification category |
|  | $<1 \%$ | Errors of two classification categories |

## Driver Behavior Summary

Data has been collected since the month of February 2005 to determine driver behavior at the test intersection. The definition of accepted gap chosen for this study is the point in time at which the rear of the minor road vehicle has vacated the minor road. At that time, the gap time is defined as the time it would take the closest vehicle to reach the middle of the intersection if its speed and acceleration were held constant. For right turns and for passage into the median, only vehicles approaching from the left are used for determining the gap. For vehicles in the median, only vehicles approach from the right are considered for the gap. Gap statistics for all accepted gaps for February and March 2005 using this definition are shown in the table below.

The mean accepted gap for every measurable driver maneuver was 10.2 seconds and the median was 9.7 s . The standard deviation was 4.1 s . For vehicles that accepted a gap less than 10 seconds, the mean accepted gap was 7.0 s and the median was 7.2 s . (If traffic volumes on the mainline are low, it is often the case that vehicles approaching the intersection are so far away that the minor-road driver does not really make a gap decision. The presence of these large gaps can skew the distribution of accepted gaps. By limiting the sample population to gaps of less than 10 seconds, the skew is removed, providing a better indication of gap acceptance decisions, under more difficult conditions.) Moreover, $95 \%$ of drivers selected a gap greater than 4.4 seconds while $99 \%$ accepted a gap greater than 3.1 seconds.

Table: Gap statistics for all accepted gaps between February 1 and March 29, 2005

| Total <br> Measured | $\begin{gathered} \text { Gaps }< \\ \text { 10s } \end{gathered}$ | Mean Gap |  | STD |  | $\begin{gathered} \text { 50\% } \\ \text { Gap } \end{gathered}$ |  | $\begin{gathered} 95 \% \\ \text { Gap } \end{gathered}$ |  | $\begin{aligned} & \text { 99\% } \\ & \text { Gap } \end{aligned}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Gaps |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| 9108 | 4808 | 10.2 | 7.0 | 4.1 | 1.9 | 9.7 | 7.2 | 4.4 | 3.8 | 3.1 | 2.8 |

Gaps were also measured based on whether the minor road vehicle was crossing/merging with northbound or southbound traffic. This analysis showed that the gaps were significantly smaller for vehicles crossing/merging the southbound lanes of US Highway 52 than for vehicles crossing/merging the northbound lanes. The average traffic volumes for northbound and southbound lanes are similar, but the traffic patterns are very different. Two signalized intersections eight miles north of the intersection in Cannon Falls cause the southbound traffic to arrive at the intersection in waves. This causes drivers to select smaller gaps when vehicles arrived in bunches because there were no large gaps available. At other times, there were no vehicles detected on the mainline so no measurable gap was recorded. The northbound lane exhibited a more steady flow of vehicles. Since the available gaps were larger and measurable, the mean accepted gap was higher.

The accepted gaps were also analyzed based on time of day. The statistics in the table below show that the smallest gaps were accepted in the evening rush hour. Zone 1 represents the area on county road 9 west of the intersection; Zone 2 represents the area on highway 9 east of the intersection. Zone 7 and 8 the area within the median, traveling east and west, respectively.

Analysis shows that the accepted gap was inversely related to the traffic volume. Traffic volume increased throughout the day and was heaviest in the evening rush hours and lightest at night.

Table: Gap statistics for different time periods of the day

| Time Period | Total Gaps | $\begin{gathered} \text { Gaps } \\ <10 \text { s } \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | $\begin{gathered} 95 \% \\ \text { Gap } \end{gathered}$ |  | 99\% Gap |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | $<1$ | All | $<10$ |
| Zone 1 | 1466 | 980 | 8.6 | 7.1 | 2.8 | 1.8 | 8.6 | 7.3 | 4.3 | 4.0 | 2.9 | 2.8 |
| Zone 2 | 2307 | 616 | 12.9 | 7.7 | 4.1 | 1.7 | 12.9 | 8.1 | 6.3 | 4.1 | 3.9 | 3.1 |
| Zone 7 | 2888 | 1449 | 10.6 | 7.3 | 4.2 | 1.8 | 10.0 | 7.5 | 4.6 | 4.0 | 3.5 | 3.0 |
| Zone 8 | 2106 | 1592 | 7.8 | 6.6 | 2.8 | 1.9 | 7.5 | 6.6 | 3.7 | 3.5 | 2.7 | 2.7 |

For vehicle type (classification) there was little difference between the accepted gap of larger vehicles and smaller vehicles. This was somewhat surprising since it would be expected that larger vehicles would need larger gaps due to their limited acceleration capabilities and their length. The definition of gap used in this work does not measure when the driver decided to take the gap, but when the driver was already committed and in the middle of the mainline lanes. This tends to normalize the accepted gap with respect to vehicle size because the definition does not measure the time it took for the vehicle to enter the major stream of traffic, which is a function of acceleration and vehicle length. The end result was that drivers of larger vehicles had a similar risk tolerance than drivers of smaller vehicles because they ended up in the middle of the intersection at the same gap time. This phenomenon will be explained further, and a new
definition may be required to support this analysis. Additional sensors may also be required to more accurately measure the point at which the driver initiates his maneuver.

The accepted gap varied based on the maneuver made by the vehicle at the minor road. The average accepted gap was largest for left hand turns, followed by right and straight through maneuvers. This was expected as it takes longer to perform a right and left turn because the vehicle must accelerate up to the mainline speed while the straight crossing maneuver only requires crossing the length of the lanes.

Table: Gap statistics for different maneuvers

| Maneuver | Total Gaps | $\begin{gathered} \text { Gaps } \\ <10 \mathrm{~s} \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | $\begin{gathered} 95 \% \\ \text { Gap } \end{gathered}$ |  | $\begin{aligned} & \hline 99 \% \\ & \text { Gap } \end{aligned}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| Straight | 6104 | 3724 | 9.4 | 6.9 | 3.9 | 1.9 | 8.8 | 7.1 | 4.1 | 3.7 | 3.0 | 2.8 |
| Right | 2945 | 1064 | 11.8 | 7.5 | 4.1 | 1.8 | 11.5 | 7.8 | 5.3 | 4.2 | 3.6 | 2.9 |
| Left | 59 | 20 | 12.7 | 6.8 | 5.0 | 1.7 | 13.1 | 6.8 | 4.4 | 4.2 | 4.2 | 4.2 |

For vehicles waiting at the stop bars on country road 9, the gap accepted decreased the longer they waited. This is due to the fact that they were waiting because there were not any acceptably large gaps. The drivers did not significantly increase their risk as the means for gaps of less than 10 seconds were similar for all waiting times.

For vehicles waiting at the median the result was different. Vehicles spending the least amount of time in the median and the vehicles spending the most time in the median chose the smallest gaps. Half the vehicles spent less than 3.6 seconds in the median.

The accepted gap data was cross-correlated with weather data collected one mile from the intersection. The average accepted gap increased for decreasing visibility and increasing precipitation rates. The average speed on the main line decreased slightly during weather events which could explain the increase in accepted gaps. Drivers chose safer gaps when the weather conditions worsened.

Finally, an analysis was done on small accepted gaps; those less than four seconds. The analysis showed that $3.2 \%$ of drivers accepted a gap of less than four seconds. Also, an over representation of small gaps was found for straight through maneuvers and for vehicles entering/merging the southbound lanes of Hwy 52. The vehicles crossing the southbound lanes of Hwy 52 from the median showed the greatest over representation of small gaps. This maneuver type exhibits the most unsafe gap selection behavior at the test intersection.

## Chapter 1: <br> Introduction

More than $30 \%$ of all vehicle crashes in the US occur at intersections; these crashes result in nearly 9,000 annual fatalities, or approximately $25 \%$ of all traffic fatalities. Moreover, these crashes lead to approximately 1.5 M injuries/year, accounting for approximately $50 \%$ of all traffic injuries.

To address the intersection crash problem, the Federal Highway Administration (FHWA) sponsored Infrastructure Consortium, consisting of Departments of Transportation (DOTs) and Universities from Minnesota, Virginia, and California, created the Intersection Decision Support (IDS) project, which was formed and given the task of developing technologies and approaches to mitigate the intersection crash problem. Three different problems are addressed as part of this initiative. Virginia is addressing signalized and stop controlled intersection violations and crashes. California is addressing Left Turn Across Path/Opposite Direction (LTAP/OD) violations, primarily in the urban and suburban setting. Minnesota has elected to address intersection crashes at rural thru-Stop intersections.

In greater Minnesota, intersection crashes comprise more than 30 percent of all vehicle crashes; in rural Minnesota, approximately one-third of all crashes occur at intersections. AASHTO recognized the significance of rural intersection crashes in its 1998 Strategic Highway Safety Plan, and identified the development and use of new technologies as a key initiative to address the problem of intersection crashes.

To clearly define the rural intersection crash problem, an extensive review of both the Minnesota Crash Database and research reports quantifying the national problem was undertaken; the results are documented in [1]. This study of 3,700 Minnesota intersections shows that crashes at rural expressway thru-STOP intersections have similar crash and severity rates when compared to all rural thru-STOP intersections. However, right angle crashes (which are most often related to gap selection) were observed to account for 36 percent of all crashes at the rural expressway intersections. At intersections that have higher than expected crash rates, approximately 50 percent of the crashes are right angle crashes (This $50 \%$ figure is up from the $28 \%$ for all rural thru-STOP intersections). Further investigation also found that drivers' inability to recognize the intersection, and consequently run the STOP sign, was cause for only a small fraction of right angle crashes, whereas gap selection was the predominate problem. This is consistent with other findings; Chovan et al. [2] found that the primary causal factors for drivers who stopped before entering the intersection were:

1. The driver looked but did not see the other vehicle (62.1 \%)
2. The driver misjudged the gap size or velocity of the approaching vehicles (19.6 \%),
3. The driver had an obstructed view (14.0 \%), or
4. The roads were ice-covered (4.4 \%).

Of these four driver errors, the first three can be described as either problems with gap detection or gap selection.

As part of a complementary State Pooled Fund Project Entitled "Toward A Multi-State Consensus on Rural Intersection Decision Support", Howard Preston and Richard Storm of CH2MHill, as part of this program, have analyzed intersection crashes in IA, WI, and NC. Both crash data and field visits were used to perform these analyses. This analysis has shown that in these states, poor gap acceptance on the part of the driver is the primary causal factor in $80 \%$ of rural thru-Stop intersection crashes. At the time this report was written, the Wisconsin report had been completed [4]; reports documenting the IA, NC, and other states will be forthcoming.

The poor gap acceptance problem can be broken down further. Gap acceptance problems are worse at night, primarily due to the limited visual cues a driver can use to judge both the speed and distance to an approaching vehicle. Furthermore, older and younger drivers are overrepresented in the rural thru-stop intersection crashes. Younger drivers suffer because of lack of experience, and as risk takers, accept gaps that are likely often to be unsafe. As drivers age, the ability to judge distances and speeds diminishes, making them increasingly susceptible to crashes due to poor gap estimation.

To address these gap related crashes, driver behavior at these at-risk intersections must be understood. As a means to understand this driver behavior, a comprehensive intersection surveillance system was designed and installed at the intersection of US 52 and County State Aid Highway (CSAH) 9 in Goodhue County, MN. This intersection was selected because

1. it was found to exhibit higher than expected crash rates [1], and
2. it was not scheduled in the near term to receive any significant treatment (i.e., a re-grade, interchange, etc.) to address the safety issues.
$\mathrm{Mn} / \mathrm{DOT}$ agreed to allow long-term testing at this intersection as a means to better understand the behavior leading to these high crash rates. This report describes the implementation of a comprehensive intersection surveillance system, and provides a statistical look at driver behavior as measured by the surveillance system. Moreover, a subset of the comprehensive intersection surveillance system consisting of the major and minor road subsystems will form the basis of an IDS system which, when deployed, will provide a driver on the minor road alerts and warnings which will indicate times and/or conditions which may lead to a crash if the intersection is entered.

## Report Organization

This report is organized into four sections: System Functional Requirements and Design, Surveillance System, System Integration, and Initial results. System functional requirements describe what functionality intersection surveillance system must provide to collect the data necessary to evaluate driver behavior. The Surveillance System section describes the mainline subsystem, the minor road subsystem, the crossroads system including requirements, constraints, and a system analysis. The System Integration section covers the synchronization and fusion of data from the three subsystems, and documents the data acquisition process and the mechanism
by which data is stored and analyzed. The Initial Results section describes the results of the analysis of the data collected at the intersection. Results to be reported include gap statistics as a function of left and right turns and straight crossings, vehicle class, time of day, and weather conditions.

## Chapter 2: <br> System Design and Functional Requirements

### 2.1 IDS Design Premise

Given the extent of the intersection crash problem and the causal factors, the IDS system will develop based on the following design factors:

In the majority of the rural thru-Stop crashes, the driver has obeyed the stop sign. This implies that the driver is cognizant of his/her situation, and that it is likely that the driver interface used at the intersection is likely to capture the driver's attention. This is a significant departure from the signal/stop sign violation problem, where the intervention system has to both capture the driver's attention and convey a timely message with substantial authority that a violation is imminent if a proper response is not executed.

With the premise that the driver's attention has been captured, the IDS system will provide a driver timely, relevant information regarding unsafe conditions. The purpose of the system is to provide this information as a means to enable a driver to make a safer decision regarding gap acceptance, but not make the decision for the driver. A prohibitive reference frame is used to lessen liability issues with indicating to a driver when it is safe to go.

Given the increasing traffic volumes on rural expressways and the need of traffic engineers to maintain or increase capacity on these roads, the IDS system should not stop traffic on the main road. The IDS system should provide the safety benefits of a signal-controlled intersection without the adverse effects on main road capacity, throughput, and congestion.

### 2.2 Technical Approach

The surveillance system described herein consists of three primary subsystems: mainline surveillance, minor road surveillance, and crossroads surveillance. Each of these subsystems can be further divided into sensor, communication, and computation components.

The surveillance system described herein serves two purposes. First, it is used to collect data that can be used to describe driver behavior at rural intersections. Because gap acceptance is the prevalent causal factor with rural thru-Stop intersections, a thorough understanding of gaps accepted by drivers is needed. To understand driver behavior, the environment in which the decisions are made must be documented and analyzed. To collect driver behavior, mainline, minor road, and crossroads surveillance systems will be used in combination with an on-site data acquisition system.

The second purpose of the surveillance system is to support the IDS system by executing threat assessment algorithms and triggering the DII with the appropriate information at the appropriate time. Providing this functionality will require only a subset of the full system described herein: the mainline and minor road surveillance subsystems and local processor that computes threat assessments and triggers the DII.

All systems described herein have been installed and tested at the Minnesota IDS test intersection, located at the intersection of US 52 and CSAH 9 in Goodhue County, MN. This system has been designed for two purposes; first, to characterize driver behavior in terms of gaps selected by drivers under various traffic, weather, vehicle, and seasonal conditions. Understanding driver behavior in these conditions is critical to the development of a DriverInfrastructure interface, which will provide a driver the needed information at the proper time. Preliminary data has shown that the AASHTO recommended gap is taken by very few drivers; the actual mean selected gap is considerably less. This information is critical if an effective, safe driver interface is to be deployed. Second, the intersection will serve as the initial deployment location for initial testing of the IDS system, including the driver interface. This rich data set collected by this intersection will enable a comprehensive "before" and "after" analysis so that the benefits of the system can be clearly demonstrated and quantified.

### 2.2.1 Driving Behavior Characterization using Roadside Sensing

The primary purpose of this task is to characterize the gaps taken by drivers for a series of maneuvers. Twelve possible vehicle trajectories occur at a four-legged intersection; interest in this program involves the eight trajectories described in Table 1 and shown below in Figure 1. These eight trajectories involve gap decisions with mainline traffic, which has been shown to be the predominant crash type at rural expressway intersections.

Table 1. Description of Trajectories of Interest for Thru-Stop Intersections.

| Starting Position | End Position | Designation |
| :--- | :--- | :--- |
| Minor A | Major A | MinAMajA |
| Minor A | Major B | MinAMajB |
| Minor A | Minor B | MinAMinB |
| Minor B | Major A | MinBMajA |
| Minor B | Major B | MinBMajB |
| Minor B | Minor A | MinBMinA |
| Major A | Minor B | MajAMinB |
| Major B | Minor A | MajBMinA |



Figure 1. Trajectories of interest for rural thru-Stop intersections.
Although trajectories MajBMinA and MajAMinB fail to be associated with a driver stopped on a minor road, driver behavior is of interest because poor gap judgments here will also lead to collisions. These trajectories and the gaps associated with them are recorded by the intersection data acquisition system. This data can be used to study LTAP/OD crashes from the mainline.

To record gaps associated with the trajectories described above, position, speed, lane assignment, and time to intersection data for the mainline traffic is needed as well. This requires the use of sensors along the mainline with sufficient coverage to compute all viable gaps for a wide range of speeds (both legal and illegal). Mainline surveillance is described in Chapter 3. Data collected by the main line also allows cross-correlation to be done, including determining gaps as a function of maneuver (i.e., left and right turns or straight across), function of approaching vehicle speed (do drivers take smaller or larger gaps as vehicles vary from the mean speed?), as well as a function of how long they have been waiting at the intersection.

In addition to simply computing gaps for the trajectories above, other factors may influence gap selection. A Road/Weather Information Station (R/WIS) provides, at 15-minute intervals,

- Visibility (in meters)
- Precipitation Intensity (light, moderate, or heavy)
- Precipitation Rate (in $\mathrm{cm} / \mathrm{hr}$ )
- Precipitation Type,
- Time Since Last Precipitation,
- Precipitation Start Time,
- Precipitation End Time,
- Precipitation Accumulation,
- 10 Minute, 1 Hour, 3 Hour, 6 Hour, 12 Hour, and 24 Hour Precipitation Accumulation.

Each of these conditions can be correlated with measured driver gaps to determine the effect, if any, each has on the driver's decision process.

The minor road sensing suite provides vehicle classification data. Generally, the larger the vehicle, the smaller its performance envelope, and therefore the longer it takes to cross or enter the traffic stream. Because the only vehicle data an infrastructure-based system is likely to have from a vehicle at the minor road is its class (i.e., motorcycle, passenger car, SUV/light truck, medium duty truck, heavy duty truck), it is important to correlate gap acceptance with vehicle size if warnings issued by the driver interface are to be timed properly and accepted by the drivers. The minor road sensing system will assign a class to a target vehicle, and that class can be correlated with the gap accepted by the driver. Statistical data associated with that correlation will provide the basis for the threat assessment and DII trigger algorithms.

Finally, the primary open questions regarding driver behavior at rural thru-Stop intersections are whether drivers stop in the median and make a second gap acceptance decision, and if they do, are the gaps accepted a function of the time spent waiting in the intersection (i.e., the longer the wait, the smaller the gap likely taken). A crossroads surveillance component is used to track vehicles as they enter and pass through the crossroads area. A thorough understanding of the driver behavior under these conditions is necessary to facilitate the design of an effective driver interface.

### 2.2.2 Surveillance for IDS Deployment

With any traffic device, cost is a serious constraint. The goal of this rural IDS project is to develop a system which can be deployed at a rural thru-Stop intersection at a cost less than a 4 way signalized intersection. In Minnesota, the cost of a 4 way signalized intersection averages $\$ 250,000$. Of course, the lower the cost of the system, the more likely it is to be widely deployed.

The primary difference between the system used to characterize driver behavior (described herein) and the surveillance system used to support an IDS system is the lack of a crossroads
component. Mainline surveillance and vehicle classification subsystems will undergo refinements to increase performance and/or reduce system cost, but these deployed subsystems will be similar and most likely simpler to those described herein.

A significant field test will be required before these rural IDS systems will see widespread deployment. As will be demonstrated in this report, the surveillance technology required for a rural IDS system is relatively mature, and could be deployed in the immediate future. What is missing, however, are an understanding of what constitutes a safe gap, what constitutes an acceptable gap, the sensitivity of these gap values to external conditions (i.e., weather conditions, traffic conditions, geographical location, etc.), and the final design of the driver infrastructure interface. Gap values and sensitivities can only be determined through extensive data collection and analysis of driver behavior at rural intersections, and is the focus of ongoing data analysis, the initial results of which are discussed in Chapter 7. The design of the Driver Interface is discussed in [3].

### 2.2.2.1 IDS System Requirements

When a crash problem is identified at a rural intersection, the traffic engineer typically has three choices:

1) do nothing (because of warrant requirements)
2) modify the traffic control, such as installing a traffic control signal
3) change the geometry of the intersection, through realignment, grade modifications, or the addition of an interchange

This list is short, but exhaustive. The toolset with which a traffic engineer has to work is quite limited in this instance. Given economic constraints, a solution attractive to a traffic engineer has to fall between items 1 and 2 above.

The primary functional requirement for the rural IDS system is to provide rural motorists a cost effective safety system which provides the right angle crash safety benefits (primarily fatal and serious injury crash reduction) of a four-way, signal controlled intersection without impeding the flow of traffic on the mainline. On a rural expressway, installation of a four-way traffic signal reduces the number of right-angle crashes, but usually increases the frequency of rear end collisions. A successful rural IDS system will reduce right angle crashes with no adverse effect on rear-end collisions. This is a tall order, but one which is achievable.

Given this goal, a specific set of top-level functional requirements can be defined. The target being set is the four-way, signal-controlled intersection. The rural IDS system must outperform the four-way, signal-controlled intersection in terms of performance, cost, and reliability

### 2.2.2.1.1 MUTCD compatibility

If the IDS system is to be deployed, the system must meet MUTCD standards and specifications. Minnesota appreciates this, and is working closely with the National Committee on Uniform Traffic Control Devices to ensure the final system meets MUTCD standards.

### 2.2.2.1.2 Operational requirements

From an operational point of view, to be embraced by traffic and highway maintenance engineers, the cost of installing, powering, maintaining, and repairing the IDS system must be compatible to that of a four-way, signal-controlled intersection equipped with both loop detectors and advanced warning flashers.

### 2.2.2.1.2.1 All weather operation

Although relatively few intersection crashes occur during poor weather and visibility conditions, these crashes still occur. An effective system will support driver decisions in all weather conditions, and as such, the IDS surveillance system shall operate regardless of weather or visibility conditions.

### 2.2.2.1.2.2 Initial purchase and installation cost

The IDS system should cost less than the cost to procure and install a conventional four way signalized traffic control system. In Minnesota, the average four way signal controlled intersection purchase and installation cost is quoted as $\$ 250,000$. The prototype IDS system, including design time, appears to cost $80 \%$ of the conventional four way signal control device.

### 2.2.2.1.2.3 Operations cost

The long term cost of operating the IDS system should be comparable to that of operating a conventional 4 head traffic signal. At this point, indications appear that operating costs should be compatible in terms of power draw and maintenance. The main controllers (computers) should draw equivalent power. The remote radar sensors will draw more current than loop detectors, but the DII should draw significantly less power than either the incandescent or LED lights in the control heads by virtue of the design of the DII and the fact that the DII is activated only when a vehicle is present on the minor road.

### 2.2.2.1.2.4 Maintenance requirements

The IDS system is designed to be low maintenance. There are no moving parts or electromechanical devices (relays) to wear out. Radar sensors are designed for heavy truck use, and have proven extremely rugged and reliable. Laser sensors are industrial sensors, specified for cold temperatures and full wash-downs. LED technology will be used wherever feasible in the DII design.

The IDS system may have higher repair costs than conventional systems in the event that a radar sensor is hit by a crashed vehicle. The mount for the radar sensor is a conventional, inexpensive 3\# U channel used by $\mathrm{Mn} / \mathrm{DOT}$ for many applications. If a radar sensor is damaged by a crash, it is likely to cost $\$ 1500$ to replace. This cost is similar to the cost of repairing an in-pavement loop detector. $\mathrm{Mn} / \mathrm{DOT}$ cites loop repair costs as $\$ 200$ to replace the splice, $\$ 300$ to replace a detector module, and up to $\$ 1000$ to replace the loop in the pavement.

The IDS system should be equipped with a self-diagnostic program. This is built into the present prototype IDS system. This is addressed in the subsystem functional requirements (section 2.2) below.

### 2.2.2.1.2.5 Reliability

Present conventional four way signal controlled intersection sets a high standard for reliability. The IDS system has to show reliability levels equivalent or better than the conventional 4 way signal controlled intersection.

### 2.2.2.1.2.6 Modular design

The IDS system should be built with a modular, open architecture. Following this guideline assures the DOT that the system will be upgradeable should improved sensors, computers, and driver interfaces become available.

Chapter 3 describes the surveillance portion of the IDS system which is designed to meet these functional requirements.

## Chapter 3: <br> Mainline Surveillance Subsystem

### 3.1. Objective

The purpose of the mainline surveillance subsystem is to determine the state of the mainline of the rural thru-Stop intersection. In this case, the state of the mainline is defined by the position, speed, lane assignment, and time to the crossroads of each vehicle on the mainline within the range of the mainline sensors. The state of the mainline, combined with the state of the cross roads and minor roads determine the state of the intersection. The state of the intersection is used by the threat assessment algorithms to determine unsafe maneuvers for the vehicles on the minor road and by the DII trigger algorithm responsible for activating the DII.

One underlying objective of the IDS program is to develop an effective, deployable system. Because state DOTs are very cost conscious, the system to be deployed must exhibit high performance:cost ratios. The cost goal of the entire IDS system is $\$ 250,000$.

### 3.2. Mainline Surveillance System Requirements

To achieve the objectives described above, the mainline surveillance system must meet a finite set of requirements. These requirements are enumerated below.

### 3.2.1 Coverage area

Although the title heading states "area," traffic engineers acknowledge that gaps are the critical element in the decision to enter or cross a stream of traffic. The use of time to characterize coverage also normalizes the analysis in terms of speed limits and known speed distributions associated with a particular intersection. The coverage requirement is based on the highest expected speed (This could be based on the $90^{\text {th }}, 95^{\text {th }}$, or $99^{\text {th }}$ percentile if a speed distribution is available for a particular intersection), a minimum acceptable gap, and the need to track vehicles to the intersection crossroads.

Using these guidelines, the coverage areas can be specified as follows. AASHTO recommends a nine-second gap as the standard acceptable gap. The physical implementation of the system may require additional time in order to achieve the requirement of being able to track a nine second gap.

For example, the present Minnesota IDS system requires 12 seconds of coverage to provide for accurate tracking at the nine-second point. One second is needed to sense an incoming vehicle by the surveillance system, and two seconds are used to track that vehicle to accurately determine its trajectory. For example, if $145 \mathrm{kph}(90 \mathrm{mph})$ is the greatest expected speed, approximately 483 m ( 1585 ft ) of surveillance coverage would be required for twelve seconds of gap estimation.

The current Minnesota IDS system is "over built" in order to determine parameters such as coverage area; it is capable of providing sixteen seconds of coverage at 145 kph ( 90 mph ). Since cost increases with coverage area, a minimum coverage area was identified after analysis of gap selection of actual vehicles. The mean accepted gap is in the range of seven seconds with the $95 \%$ gap time above four seconds. A deployed IDS surveillance system should implement a coverage area in the range of the mean accepted gap time, and must include a time buffer for drivers at the minor road to respond to the DII as well as to accommodate large slow-moving vehicles. For the test intersection described herein, the current sixteen second coverage could be reduced to thirteen seconds for an optimized IDS system (average gap of 7 seconds +3 seconds for tracking +3 seconds time buffer).

### 3.2.2 Continuous tracking

The mainline surveillance system must track vehicles all the way to the intersection crossroads to ensure anomalous situations are covered. For example, a vehicle may pull over to the shoulder after entering the coverage zone, but before reaching the crossroads. When that vehicle pulls back into the mainline traffic, it must be tracked to assure agreement between what the minor road driver sees and what the DII tells the driver. If a vehicle were close, but not sensed by the system, a driver would not be alerted to a potentially dangerous situation, thereby eroding confidence in the system.

### 3.2.3 Accuracy

Speed accuracy should be better than 2 MPH (3.2 KPH), lateral position sensing accuracy should be 4 feet ( 1.2 m ) to ensure proper lane assignment, and longitudinal accuracy should be $+/-40 \mathrm{ft}$ (22.9m) to accommodate "masking" arising from large vehicles shadowing smaller vehicles because sensors are mounted on the side of the road (see Figure 23). Lane level accuracy is important from the standpoint of crash and gap analysis; differentiation between traffic traveling in the left and right lanes affects the gap acceptance decision made by the driver; a driver will often, but not always, move into the mainline if the rightmost major road has an reasonable gap, even if the left lane has an unsafe gap. Differentiation of lane occupancy is needed to fully characterize gap acceptance decisions.

### 3.2.4 Fault Detection/Fault Tolerance

Due to the safety critical nature of the IDS system, it must be designed to detect faults, and operate in the presence of faults. The mainline sensor system has been designed to detect faults, and to be fault tolerant. This capability is achieved by using multiple sensors in conjunction with a Kalman filter based vehicle tracker and a communication module to check the status of the remote mainline sensors. A description of the fault tolerance/fault detection capabilities are described in the performance specification section of the report.

### 3.3. Constraints

As part of this design, Mn/DOT did place a few constraints on the system. These constraints are enumerated below.

### 3.3.1 Proximity to Highway

No sensor shall be mounted closer than 12 feet to the road-shoulder.

### 3.3.2 Low Voltage

Any sensor located in the clear zone (the clear zone is defined as any location within 30 feet of the road-shoulder) must be supplied with direct current of less than 15 volts.

### 3.3.3 Break Away

All fixtures must meet state and federal breakaway standards. All electrical equipment located in the clear zone must be equipped with breakaway electrical connectors.

### 3.3.4 Restriction in Median

No equipment shall be located in the median of the expressway. This is because equipment mounted in the median is frequently hit by traffic.

### 3.4. System components

The mainline surveillance subsystem provides three primary capabilities: sensing, communications, and computation. A wide variety of candidate sensors that can provide vehicle position, speed, lane of travel, and time to intersection are available. Candidate sensors are described below, with the choice of radar justified.

Because the choice of sensor has a significant impact on the design of the surveillance system, a survey of sensors and the rationale for choosing radar is describe in section 0 below. Communication and computation are subsequently discussed in section 0 and 0 .

Communication choices are limited to both wired and wireless system. Tradeoffs associated with each are discussed below, as is the approach taken in the rural IDS system.

### 3.4.1 Sensors

For the mainline, both point detection and continuous detection sensors are available. Point detectors include inductive loops, cameras, and laser diode retro-reflective presence detectors. Continuous detectors include radar and camera arrays.

Point sensors were ruled out early because of the need of the rural IDS system to track vehicle trajectories. Traffic speeds vary widely on rural highways, from extremely low speeds in poor weather and low visibility to high speeds driven by speeders in a hurry. A safety system must accommodate this distribution of speeds. As such, discrete speed/location data is insufficient to accurately estimate a vehicle trajectory. The limitations of point detectors for estimating vehicle trajectories were also documented by VTTI research (See 0). Point detectors offer little or no cost advantage over continuous sensors, yet provide less information. Thus, continuous sensors are the primary point of discussion.

Visible light and infrared cameras were evaluated as potential mainline sensors. Traffic monitoring cameras offer a limited field a view; this limitation makes applicability to mainline surveillance difficult on many fronts. Accurate estimation of a vehicle trajectory requires, at the very least, a few seconds of accurate tracking. To achieve two seconds of tracking would require a camera with a large field of view mounted high over the mainlines or an array of multiple cameras mounted near the roadside. The wide field of view approach reduces the resolution with which a vehicle can be detected, making robust tracking in difficult light conditions complicated. Using an array of multiple cameras along the roadside results in high costs in terms of both processing power and infrastructure. To avoid glare from vehicle headlights, cameras would have to be installed well above the road surface. Supporting infrastructure adds to both the cost and complexity of the system. Performance limitations and infrastructure costs make this a poor design choice.

Radar has been used in many traffic engineering applications. Functional requirements specify that the surveillance system provide lane of travel information for the vehicles detected by the surveillance system. Radar designed for traffic monitoring use very narrow horizontal fields of view (width of sending cone is less than one lane width at maximum range), and are typically mounted on overhead gantries, with one sensor per lane. Because of the lack of available overhead structures on which conventional traffic radar can be mounted at rural intersections, their applicability was discounted.

New generation automotive radar can provide range, range rate, and azimuth angle to multiple targets (up to 8 targets). A priori knowledge of the road geometry combined with the sensing capability allows the sensor to provide the information needed to meet system requirements.

Three radar sensors offering the range, range rate, and azimuth information were evaluated: the Eaton Vorad EVT 300, the Autocruise LR, and Delphi ACC 3 radar.

The Virginia Tech Transportation Institute (VTTI), as part of the IDS program has done an exhaustive analysis of the Autocruise radar [5]. Performance specs for the Autocruise LR radar are provided below:

Operating Frequency: 76 GHz
Max Range: 150m (492 ft)
Range Rate: accuracy: better than $0.2 \mathrm{~km} / \mathrm{hr}(0.12 \mathrm{mph})$
Azimuth: 12 degrees, precision 0.3 degrees
The VTTI reports that the maximum range of the Autocruise Radar in practice exceeds 182 m (600ft), and that it has detected vehicles at nearly 304 m (1000ft).

An Autocruise radar sensor was not purchased and evaluated for three reasons. First, VTTI performed an extensive analysis of this sensor, and that work need not be repeated. Second, the Autocruise radar is expensive at $\$ 4,500$, and given VTTI's analysis of that the sensor, the Autocruise radar fails to offer performance:cost benefits over the Eaton EVT-300 sensor. Third, the operating frequency of 76 GHz is susceptible to energy absorption problems in humid, wet, or snowy conditions, which is problematic for Minnesota applications.

The Delphi ACC 3 radar offers similar performance / price specifications to the Autocruise radar. A request for bids (RFB) in April, 2004, was posted to acquire the radar equipment needed to populate its prototype intersection. Delphi responded after the RFB closed, but agreed to sell the University of Minnesota three units for evaluation. A PO to acquire 3 units was issued in June 2004, Delphi delivered three prototype units at the end of October 2004. Given the delayed acquisition date, an analysis of the Delphi radar unit was not finished at the time of the writing of this report. The analysis will commence in the Spring 2005.

The performance specs claimed by Delphi for the ACC 3 radar is as follows:
Operating frequency: 76 GHz
Max Range: 150m (492ft)
Range Rate: -198 to $+36 \mathrm{~km} / \mathrm{hr}$ accuracy $\pm 1.8 \mathrm{~km} / \mathrm{hr}$ ( -123 to $22 \mathrm{mph}, \pm 1.1 \mathrm{mph}$ )
Azimuth: 15 degrees, precision 0.5 degrees
Update rate: 10 Hz
These units cost \$3,330, and are significantly more expensive than the Eaton units. When time permits, they will be co-located with the Eaton sensors, and judged using the Eaton as a reference sensor. Of primary concern is the performance of the sensor in humid, wet, or snowy conditions because of the 76 GHz operating frequency.
The radar sensor of choice (so far) has been the Eaton Vorad EVT-300. The claimed performance specifications of the EVT-300 is as follows:
Operating frequency: 24.5 GHz
Maximum Range: (107m) 350ft

Range rate: 0.8 to 162 kph ( 0.5 to 100 mph )
Azimuth: 12 degrees, resolution 0.2 degrees
Maximum range error: 5\% of reported range
Data rate: 10 Hz
Maximum targets detectable: 8
The EVT-300 was subject to an extensive performance evaluation in the context of a roadside sensor [6]. In [6], the performance claims of the EVT-300 were found to be conservative, especially maximum range, which was found to be approximately 134m (440ft).

From the perspective of an IDS system, the EVT-300 is a preferred sensor. First, it is readily available, and significant support is available. Second, it offers documented all-weather performance [7] at an operating frequency of 24.5 GHz ; sensitivity to atmospheric moisture remains an unknown for sensors operating at 76 GHz . Third, it is one-third to one-fourth the cost of competing sensors, making it attractive from both the initial investment and replacement cost point of view.

It should be noted that all three radar are designed for automotive use. As such, there are very few differences in mounting hardware, and electrical and communication interfaces. Because all three are designed to survive automotive applications, durability and reliability performance would be expected to be similar.

### 3.4.2 As Built Mainline Surveillance System

### 3.4.2.1 Architecture and data flow

### 3.4.2.1.1 Sensor Layout

Surveillance on the mainline requires a large area of coverage as well as accurate speed and position sensing. Experiments with the EVT-300 radar [6] provided evidence that radar was best suited for this purpose.

The EVT-300 radar exhibits a maximum range of 134 m (440ft) and performs satisfactorily when placed 7.9 m ( 26 ft ) away from the lane-center with a small sensor orientation angle (The sensor orientation angle is the angle between the normal to the radar antenna and the road.) [6]. This allows placement of the radar antenna 3.6 m (12ft) away from the road shoulder and yields good performance with tracking targets on a two-lane highway (The lane adjacent to the median (disregarding turn lanes) will be referred to as the outer lane; the other lane will be referred to as the inner lane.).

Figure 2 illustrates the sensor placement for the US 52 Northbound (NB) \& US 52 Southbound (SB) sections of the Hwy52 intersection site. The current system consists of 7 EVT-300 radar
units (R1-R7 \& R8-R14) facing the traffic on each of the two sections of road. The coverage provided by sensors R7 and R14 determine vehicle trajectories beyond the intersection. These sensors provide information (i.e., acceleration rates, interaction with mainline traffic) regarding traffic entering the mainline from the minor road. Table 3 illustrates the lane coverage area for the sensor configuration being used. The total lane coverage preceding the crossroads is 655 m ( 2150 ft ) and 107 m ( 351 ft ) beyond the crossroads. This allows the system to track a vehicle traveling at $137 \mathrm{kph}(85 \mathrm{mph})$ for 17.2 seconds. (The speed limit at this section is 105 kph (65mph).)

Because of the constraints on the placement of the radar sensor (must be 12 feet from the road shoulder, cannot be mounted in the median (see section 3.3 on page 13)), small gaps in coverage are unavoidable if the cost is to be reasonable. To compensate for these gaps, a target tracker module has been developed that identifies each vehicle leaving the radar sensor coverage, and estimates the position and velocity for the period of time that the identified vehicle is not within the field of view of the radar array. The coverage gaps listed in Table 2 and Table 3 are indicated in red in Figure 2. Gaps in the lane coverage are tolerated in order to keep the sensor orientation angle as parallel to the road as possible, and to minimize the number of sensors. The average sensor orientation angle for the current configuration is $4.9^{\circ}$; this ensures good accuracy from the sensor [6].


Figure 2. Radar Coverage along mainline at the Hwy52 intersection.

Table 2. Theoretical Mainline Lane Coverage up to intersection.

|  | Hwy52 North <br> $\mathbf{m ~ ( f t )}$ | Hwy52 South <br> $\mathbf{m}(\mathbf{f t})$ |
| :--- | :---: | :---: |
| Lane Coverage | $655(2150)$ | $655(2150)$ |
| Total Coverage Gaps (Inner Lane) | $91(298)$ | $85(279)$ |
| Total Coverage Gaps (Outer Lane) | $195(640)$ | $189(620)$ |

Table 3. Mainline Lane Coverage beyond intersection.

|  | Hwy52 N <br> $\mathbf{m ~ ( f t ) ~}$ | Hwy52 S <br> $\mathbf{m ~ ( f t ) ~}$ |
| :--- | :---: | :---: |
| Lane Coverage | $107(351)$ | $107(351)$ |
| Total Coverage Gaps (Inner Lane) | $0(0)$ | $0(0)$ |
| Total Coverage Gaps (Outer Lane) | $23(75)$ | $23(75)$ |

With the knowledge of the sensor range and required orientation angles for the sensors, the layout shown in Figure 2 was designed. An in-house developed design tool (See Figure 3) was used to place sensors and evaluate the coverage achieved with various sensor configurations.


Figure 3. The design tool used to test various sensor placement configurations.

### 3.4.2.1.2 Sensor Mounting

The radar antenna mount provides three degrees of freedom: pitch, yaw, and height. (Figure 4). The mount attaches to standard 3 lb . "U" channel (flanged channel) signposts provided by $\mathrm{Mn} / \mathrm{DOT}$; the sensor is positioned 15 " above the road surface. At this height, the radar can detect vehicles from sedans to tall vehicles such as semi-trucks. After the sensor mount is in place, the sensor is aimed horizontally and vertically, and calibrated (procedure described under the 'Implementation' section).


Figure 4. Radar mount antenna assembly. (Dimensions in inches.)

### 3.4.2.1.3 Communication

### 3.4.2.1.3.1 Radar Sensor Station Hardware

Each sensor on the mainline is connected to an individual data processing computer in an adjacent cabinet. Because the radar operates on "low" voltage (7.3 VDC), the radar antenna itself can be placed close to the road ( 3.67 m ( 12 ft ) from the road shoulder). Because it operates at high voltage ( 120 VAC), the actual processing hardware is kept outside the Mn/DOT specified clear zone ( 9 m ( 30 ft .) from the road shoulder), as shown in Figure 5. Power and data communication
to the radar antenna is provided by cable run in a conduit underground. The radar station signal flow diagram is shown in Figure 6.


Figure 5. Sensor Station Layout.


Figure 6. Radar Sensor Station Dataflow.

The EVT-300 radar uses the J1708 protocol for data communication; J1708 is converted to RS232 before being fed to the radar pre-processor computer. This computer executes the radar
interface (i.e., driver) and then converts the range and range-rate data provided by the radar into state-plane coordinates used by the vehicle tracking system. This state-plane data is then sent to the main processing computer via an Ethernet-DSL network. Because the distance between most radar stations to the main controller is more than 152 m (500ft), the signal needs to be amplified (the recommended maximum distance or twisted pair Ethernet is 100 m (328ft).) A very high bitrate Digital Subscriber Line (VDSL) modem is used in the sensor cabinet and the main controller cabinet, allowing the two units to communicate over a separation of 1 mile. The main cabinet contains hardware to collect all the VDSL lines from all the mainline sensor stations; the main controller cabinet is described below.

### 3.4.2.1.3.2 Main Controller Cabinet Hardware

Every sensor station on the mainline is connected to the main controller cabinet using an Ethernet-DSL network. Each station has a dedicated CAT 5 cable connected to the main controller. The main controller cabinet contains two racks of VDSL modems that convert the signal from the sensor station DSL modem back to standard Ethernet. This is then connected to the Ethernet switches and routed to controller computers.

Three computers are located in the Main Controller Cabinet. The first computer processes all mainline and minor road sensor data; the second computer acts as a timeserver for all the remote sensor station computers, and the third computer processes video data used to monitor the crossroads median (See Figure 7). The details of the processes on the main processing computer are discussed in the 'Processing' section below.

The timeserver uses a Trimble Accutime ${ }^{\text {TM }} 2000$ Time Synchronization GPS unit and the Network Time Protocol (NTP) to synchronize all internal computer clocks on the network to Coordinated Universal Time (UTC). The NTP module synchronizes the time of computer clients anywhere on the network with accuracies typically in the order of a few milliseconds. A NTP server module runs on the timeserver computer; client modules run on all the sensor processing computers that request the time from the server. The NTP module estimates network latency and other delays in order to set the time on the client side. This allows all the sensor data to be accurately and consistently time-stamped before it is sent to the main controller.

Figure 8 illustrates the overall dataflow diagram for all the mainline sensors. Each sensor receives time synchronization signals from the timeserver and this is used to timestamp the preprocessed radar sensor data. The details of the processing are discussed in the next section.


Figure 7. Main Controller Cabinet Hardware.


Figure 8. Mainline Communication Dataflow Diagram.

### 3.4.2.1.4 Processing

### 3.4.2.1.4.1 Sensor Station Local Processing

Radar sensor data pre-processing is performed by the PC104 computer located at each radar sensor station. Figure 9 shows the dataflow between various processes in the sensor station. Each sensor station processor can support two radar sensors; this can be increased to 6 sensors using an additional serial card. The sensor station computer sensor driver process initializes the sensor and reads raw sensor data at 10 Hz . Raw data in the sensor coordinate frame is converted to state-plane coordinates based on the sensor location and orientation (see Figure 10). For the Minnesota intersection, south state plane coordinates are used.


Figure 9. Radar Sensor Station Dataflow.

A previously mentioned, each data set is time stamped before being transmitted to the main controller; this allows the vehicle-tracking module in the main controller to account for all time lags in the data transfer process. An NTP client running in the background ensures that the sensor station clock and the main controller clock are synchronized.


Figure 10. Coordinate Conversion - Sensor Coordinates to State-Plane Coordinates.

### 3.4.2.1.4.2 Central Processing

A central process in the main controller gathers the data from each sensor on the mainline, groups it, and sends it to the vehicle-tracking process. Figure 11 shows the data flow for the sensor collector process. The same process also gathers data from the other sensors on the minor road and the crossroads so that that intersection state can be computed. The sensor collector process also has the ability to monitor sensor condition and report the sensor status.


Figure 11. Sensor Collector Process at the Main Controller (Mainline Sensors).

## Vehicle-Tracking/State Estimation

Estimation of the intersection state requires a vehicle-tracking module that continuously estimates the position, lane assignment (derived), speed, acceleration, and heading of each vehicle within the boundaries of the intersection. This state information, combined
with intersection geometric information enables determination of each vehicle's time to intersection, or gap time, which is the time that each vehicle would arrive at the intersection if its speed were held constant.

Functional requirements for the tracking module include:

1. Continuous tracking of all vehicles in the system.
2. Assignment of unique Identification numbers (ID) to each vehicle in the system. The ID must be maintained for that vehicle within intersection boundaries, even if the target changes lanes or makes a turn.
3. Provision of vehicle position (Lane number as well as location in the lane.)
4. Provision of vehicle velocity
5. Provision of vehicle acceleration
6. Provision of vehicle time to intersection and hence lane gaps
7. Assignment of regions of travel (to ease the post-data-processing.)

The vehicle-tracking module is responsible for the construction of the real time state of the intersection. This intersection state data forms the basis of all the data processing done to study driver behavior, and will be used to determine the type and timing of driver warnings once the Driver-Infrastructure Interface is designed and installed at the intersection.

## Sensor Data Pre-Filtering

In order to produce an accurate, timely estimate of the state of the intersection, raw sensor data has to be filtered and "aligned" temporally (see Figure 12). Raw data is first filtered with respect to three parameters: speed, heading, and road geometry. Because all sensors operate independently (computers are synchronized, but sensors are not), sensor information has to be aligned temporally to represent the intersection at precise 100 ms intervals. The filtering and alignment processes, all of which are performed on the main system processor located at the main cabinet, are described below.

Filtering. The first filter removes outliers based on target speed. Targets moving too slowly ( $<2 \mathrm{~m} / \mathrm{s}(4.5 \mathrm{mph})$ ) on the mainline are removed from consideration. The radar only detects moving targets due to its reliance on the Doppler effect; stationary objects are not detected. With strong winds, signposts oscillate fast enough to be sensed by the radar. The sensed speeds of the oscillating signs are low and therefore easily identifiable. They are therefore removed from the data set.

The second filter processes vehicle heading. Sensor data from vehicles heading toward or leaving the intersection are accepted; all other data are discarded. This eliminates the chance that false targets or animals crossing the roadway are not identified as a valid target.

The third filter ensures that valid targets are located on the road. This filter compares the location of identified targets with the landscape local to the sensor. The landscape is represented by a geospatial database [8,9], which describes the geometry of the roadway and locates other hard elements within the boundaries of the intersection. The geospatial database contains location and attribute information about lane-centers, lane-boundaries, road-islands, road-shoulders, guardrails, etc. The database information is provided through a server process that responds to application driven requests for data. Upon initialization, this filter module requests lane center information for all intersection lanes, and converts this to its own format to be used to filter targets outside the lanes. If the radar detects a target to be within $1.2 \mathrm{~m}(4 \mathrm{ft})$ of the lane-center, it is considered to be in that lane; if it is outside this threshold, it is either in the adjacent lane or on the shoulder.

Temporal alignment. After the data has been filtered, a reduced set of valid targets is obtained ( $n$ unfiltered targets are reduced to $m$ targets as shown in Figure 12). Since each sensor acts independently, target information is not provided at the exact same time. This creates a time lag and compensation must be made to bring up to date and synchronize the data to the current time. This time lag is the time difference from when the sensor last detected a target plus transmission time, and is estimated by measuring the time difference between the update step (time at that moment) and the sensor-station timestamp for that sensor measurement. Typically measured lag was under 60 ms .

Using past measurement state data (position and velocity), the new measurement state is calculated by estimating a new state at a future time using the calculated time lag for each measurement. The resultant table contains an estimate of the measurements at the current time step. This data is then used in determining the system state at the current time step.


Figure 12. Filtering and temporal alignment of sensor data.

## State Estimation

The state estimation process involves the representation of the intersection at two discrete times: the previous estimated state (at time t) and the current estimated state (at time $\mathrm{t}+\mathrm{t}$ ). Intermediate to these two discrete states is a projected state which represents the intersection state based on the projection ahead to time $t+t$ of known trajectories from time t (See

Figure 13). The vehicle tracking process updates the current estimated state of the intersection in the 'Known Targets Table' at 20Hz. The projected state is matched with the filtered measurement at time $t+\Delta t$ to obtain the current estimated state at time $t+\Delta t$. During the process to match measurements with the projected state, three outcomes are possible:

- New Target Identification. A subset of the filtered measurements is not matched with any of targets in the projected state (highlighted in blue in
- Figure 13).
- Target Measurement Update. A subset of the projected state is matched with a subset of the filtered measurements.
- Missed Target. A subset of the projected state is not matched with any of the filtered measurements, but has not been missing for more than eight seconds. (highlighted in dark green in
- Figure 13).
- Exiting Target. A subset of the projected state is not matched with any of the filtered measurements and has been missing for more than eight seconds (highlighted in red in
- Figure 13).

New Target Identification. Measurements that do not match any of the targets in the projected state lead to the creation of a new known target that is added to the 'Known Targets Table'. The target is assigned a lane, lane longitudinal position, velocity, distance and time to intersection, as well as other parameters used for estimation purposes. The new target is also assigned a unique identification number that maintains its association with the target until it moves outside the intersection boundaries and is no longer tracked. This ID number is used in the post-data processing to determine the vehicle trajectory while it is within intersection boundaries. The ID number uses the format yyyymmdd.XXXXX, where X is an integer between 0 and 9 . One hundred thousand unique IDs can be created everyday. Because the ID is associated with a single vehicle, vehicles assigned an ID at the end of a day carry the same ID into the next day if the vehicle is within the boundaries of the intersection at midnight.


Figure 13. State Estimator Data Flow.
Blue targets represent the appearance of new targets, the red target represents a target which has exited the intersection, and the dark green target represents a masked target which is assumed to have not exited the intersection.

Target Measurement Update. Targets in the projected state that match a subset of the measurements are previously known targets that are still in the system. These targets will continue to be tracked and an update step is performed, wherein the parameters for the target state are updated with new measurements.

The measurements are checked to see if the vehicle moved to an adjacent lane and the lane and lane position are correspondingly adjusted. Because the radar sensor tends to pull targets toward its longitudinal axis (discussed in section 0 below), targets traveling on the outside lane may be "pulled" into the inside lane briefly. To avoid lane classification errors, a history of the last three measured lane positions is maintained. If a target was seen in this new lane for the last three measurements, then it is allowed to change lanes. If not, then the target is forced to remain in the same lane that it was traveling in (See Figure 14).

```
Considering time step t
    If,
        \(L_{H}^{k}(t-\Delta t)=L_{H}^{k}(t-2 \Delta t)=L_{H}^{k}(t-3 \Delta t)\)
    then,
        \(L^{k}(t)=L_{H}^{k}(t-\Delta t)\)
Otherwise,
    \(L^{k}(t)=L^{k}(t-\Delta t)\)
                where,
                            \(L_{H}^{k}\) - Lane history for target \(k\)
                            \(L^{k}\) - Current lane for target \(k\)
```

Figure 14. Checking the lane history before making a lane change.
Missed Target. Targets in the projected state that did not match any of the measurements are stored in the 'Known Targets Table' and are kept and used in subsequent time steps if the target has not been missing for more than eight seconds. If the target has been missing for more than eight seconds, it is assumed to have exited the intersection boundaries.

Exiting Target. Every target that enters the system must exit the system at some point in time. After the projection step, if the target has not been matched with any of the sensor measurements for the more than eight seconds, it is deleted from the 'Known Targets Table'.
3.4.2.1.4.3 Radar Behavior Effects associated with application of vehicle-based radar for intersection surveillance systems

The EVT-300 radar is designed for vehicle-based forward collision warning - the sensor is designed to be mounted at the center of the vehicle at a height of approximately 38 cm ( 15 in ). The internal radar software is optimized for the detection of targets directly in front of the
vehicle; to minimize the probability that a target is missed, targets tracked off-axis are "pulled in" and handled as if they were on-axis.

Because of constraints associated with the roadside mounting of radar sensors (mounted no closer than 12 ft to the road-shoulder), all vehicles tracked by the radar are off of the main axis of the sensor, and therefore subject to "pull in." The effect of this "pull-in" results in what appears as an abrupt lane change. This abrupt lane change is physically impossible as it represents a maneuver outside of the dynamic performance envelope of any road-going vehicle. Moreover, this "pull-in" occurs in a small geographic region, and is therefore deterministic. Because it is deterministic, a process to compensate for this behavior has been developed.

Figure 15 shows a plot with a target moving along the mainline across a radar unit. The gray arrow represents the direction of travel of the radar target. The radar targets (shown as blue dots) start out on the lane, but leave the lane as the target approaches the radar. (See $(\mathrm{X}, \mathrm{Y})=$ $(10,250)$.) Various compensation equations were evaluated; the performance of the compensator currently used is shown on the plot (black + ). This compensation places the target correctly on the lane and keeps the position accuracy high (see Performance section).


Figure 15. Compensation for "pull-in" effect. Gray arrow represents vehicle trajectory.

### 3.4.2.1.5 Implementation

### 3.4.2.1.5.1 Sensor Aiming

Once the sensor mount is attached to the $3 \# \mathrm{U}$ channel (Figure 16), the antenna needs to be aimed and calibrated. An accurate aiming procedure is described under the EVT-300 evaluation process. Calibration and aiming has to be performed for all the sensors on the mainline. This method was tedious until visualization tools were developed. The visualization tool draws the sensor's region of coverage, the digital map, raw sensor data and tracked target data in real time in a top down view.


Figure 16. Radar antenna mounted on flanged channel.
The antenna can be accurately aimed by visually correlating sensor data in coordinates to actual vehicle position. The procedure involves first adjusting the desired yaw angle for the sensor using the design tool (See Figure 3 on page 18) used to design the surveillance system. With this yaw angle set and the coordinates of the sensor antenna known, raw sensor data from the radar antenna was converted into state-plane coordinates and plotted with respect to the intersection map. Using the visualization tool, the plotting can be performed in real-time at the work site (wired or wirelessly). When a vehicle approaches the radar antenna, the position determined by the radar and visualized on the screen is compared to the actual location of the vehicle on the
roadway. Because the desired azimuth angle of the sensor was previously determined by the design tool, aiming is as simple as rotating the sensor until the radar data drawn on the visualizer (in state-plane coordinates) matches the lane and trajectory of the actual vehicle passing by the sensor.

Because vehicles frequently pass by at the test intersection, this process is rapidly performed.

### 3.4.2.1.5.2 System Performance

Individual sensor performance has been documented in [6], and for convenience, the paper is included in Appendix A.

## Overall Mainline System Performance

Vehicle Detection Rate Tests. In order to evaluate the reliability of the mainline surveillance system an experiment was conducted to cross reference tracking results with a laser trigger and camera. A three-sensor suite of single beam lasers was used to determine the precise moment a vehicle passed a particular point on highway 52. The laser sensors triggered an image capture of that area of road. The trigger time stamp was compared with the mainline tracker to determine if the vehicle was detected. When an undetected vehicle was found the image for that vehicle was examined to make sure there actually was a vehicle on that section of road.

Three retro-reflective laser sensors were mounted on a vertical pole with their respective reflectors positioned across the road in the median (Figure 17). These sensors detect beam interruption, and respond to the beam interruption in less than 2 ms . This provided a reference measure of every vehicle passing the section, and was compared to the detection of the mainline surveillance system. The use of three retro-reflective sensors can account for variations in the height of vehicles approaching the test area (i.e., a single sensor mounted low or high may not have its retro-reflective beam interrupted. Multiple sensors minimize the frequency of that occurring.)


Figure 17. Three Retro-reflective sensors mounted on the same vertical plane.
The sensors were placed below a camera mounted on a (separate) tall mast. These camera captured images were used in the data analysis to verify the presence of targets should a discrepancy arise among the laser triggers and the mainline surveillance system. Figure 18 shows a data flow diagram for the vehicle detection experiment.


Figure 18. Dataflow diagram for the vehicle detection rate experiment.

Before starting the experiment, it is necessary that the clocks of all the computers are synchronized (using the timeserver). The retro-reflective sensors provide a digital signal when the beam is crossed; the digital IO card on the controller computer detects this signal. If two of the three retro-reflective sensors report a target, then a trigger signal is sent to the video capture computer and an image from the camera placed above the sensors is captured. The imagecapturing computer also records the timestamp of the vehicle crossing; this is used to query the recorded mainline processed data to find a match for that target. Figure 19 shows the view from the overhead camera when a vehicle is passing through the beam (virtual laser beam overlaid on image).


Figure 19. View from the overhead camera (laser beam overlaid on image for illustrative purposes).
When the data was processed, a search area of 30 m around the "hit point" of the vehicles was used (see Figure 20). This search area allows for flexibility with position errors, and signal acquisition and transmission lags between the retro-reflective controller computer and the imagecapturing computer. Data collected over a three-day period indicated 51,942 laser scanner crossings and 51,930 radar detections. The images for the twelve misses were analyzed, and it was found that only five of those twelve were actual missed targets giving a detection rate of $99.990 \%$. The other seven "misses" were probably due to false triggering of the retro-reflective sensors. In the analysis of the five misses, it was found that if the search area was increased to 35 m , there was only ONE valid miss. With just the one miss, the vehicle detection rate of the system is $\mathbf{9 9 . 9 9 8 \%}$.

It should be noted that this detection rate is for a single radar station. Multiple radar stations positioned along the road provide redundancy in the unlikely event that one radar station misses a vehicle; other radar stations along that road will detect that vehicle at the $99.998 \%$ rate. The system detection should greatly exceed the $99.998 \%$ figure above.

Because of sensor location constraints (i.e., no sensors in the median areas), the detection rate drops when vehicles are masked either laterally or longitudinally (Examples shown in Figure 21 and Figure 22). However, this does not affect system performance, as the gaps are not classified by left lane gaps or right lane gaps. The vehicle closer to the crossroads represents the primary threat to the driver, and warnings are computed accordingly, thereby not affecting system performance.

Preliminary testing using DGPS equipped probe vehicles shows that if vehicles are separated longitudinally by more than 16 m ( 53 ft ), the radar will detect and track both vehicles $99 \%$ of the time (at one standard deviation). The vehicle closer to the intersection will be detected at the $99.998 \%$ rate described above. This does not adversely affect the performance of the IDS system.


Figure 20. Search Zone around the laser beam hit point.


Figure 21. Lateral masking - Green target masks violet target.


Figure 22. Longitudinal masking Green target masks violet target. Vehicle separation denoted by X.

Mainline System Speed and Position Estimation Accuracy Tests. Tests were conducted to determine the accuracy of the mainline system in terms of vehicle speed and lateral and longitudinal position in a lane. The tests were performed using two probe vehicles fitted with high accuracy, differential corrected GPS (DGPS). A local base-station at the main controller cabinet provided the DGPS corrections for the probe vehicles ensuring that the position accuracy of the GPS system is within 5 cm [10].

Each probe vehicle contained an 802.11b wireless client that received time synchronization signals from the main cabinet to keep a record of DGPS data with an accurate timestamp. A dataflow diagram for the experiment is shown in Figure 23.

A sedan and a truck served as probe vehicles. This mix facilitated quantification of the differences in accuracy for the two vehicle types. The probe vehicles were driven along the mainline, changing various parameters with each run: speed and lane of travel. The longitudinal time error, longitudinal position error (meters), lateral position error (meters) and speed error were measured for each GPS position measurement (Figure 24).


Figure 23. Dataflow for the mainline probe-vehicle experiment
For each run, the DGPS data was compared to the mainline surveillance system data to determine mainline surveillance system position and speed estimation errors. Figure 25 and Figure 26 show the error plots from runs with the sedan as well as the truck traveling on a single lane. The three graphs shown in the figures represent the longitudinal time error, longitudinal lane position errors and lateral lane position errors for the runs (Figure 24 defines the errors). The longitudinal time error is the estimated time difference between the system state reported position of the probe vehicle and the actual vehicle position as reported by the DGPS system. This error is measured by dividing the longitudinal lane position error by the speed of the probe vehicle. This error, along with the speed estimation error, was used to calculate the time to intersection (gap time) error.

It can be seen from the plots that longitudinal time errors are usually less than 250 ms . The longitudinal time error directly affects the measurement accuracy of gaps and hence, the worstcase error in gaps caused by longitudinal position error would be 250 ms . The longitudinal lane position error follows the same curve as the longitudinal time error and this error is usually less
than 8 m . Comparing the two plots, the truck has larger longitudinal position errors than the sedan. This is due to the ambiguity of the detection region of the radar on the vehicle. Larger vehicles demonstrated larger longitudinal position errors. For a more detailed explanation of this phenomenon see the paper containing the EVT-300 performance evaluation experiments [6].


Figure 24. Definition of errors that were measured for the probe vehicle tests.
Longitudinal accuracy degraded to no worse than 23 m should a vehicle be masked either laterally (on the left side of a larger vehicle (see Figure 21) or longitudinally (following closely behind a leading vehicle (see Figure 22)). Preliminary testing using DGPS equipped probe vehicles shows that if vehicles are separated longitudinally by more than 16 m ( 53 ft ), the radar will detect and track both vehicles $99 \%$ of the time. The vehicle closer to the intersection will be detected at the $99.998 \%$ rate described above. It is important to note, however, that masking does not degrade the performance of the IDS system as gaps are defined in terms of both lanes, and not a left lane gap and a right lane gap. The vehicle closer to the radar will be tracked, and therefore the gap measure will be conservative.

The lateral lane position error determines the lane classification accuracy; this is usually less than 1 m . For a target to be correctly placed in the right lane, this error should be less than 1.2 m [6]. The RMS lateral error for the sedan was 0.22 m and 0.92 m for the truck. Clearly the surveillance system is able to correctly detect the lane of travel of traffic most of the time. The plots in Figure 27 and Figure 28 illustrate how the lateral error grows when a lane change is made. To ensure that false lane changes are not made, the vehicle-tracking module does not enforce a lane change until the target is well into the new lane. This causes the large lateral errors
and as soon as the lane change is complete, after which the errors drop back to their normal state. Lane classification ambiguity typically occurs only during lane change maneuvers.

It should be noted that the goal here was to determine how accurately the surveillance system could track real traffic. It would be trivial to add a time lead term that would force the estimated longitudinal vehicle position (and time) to lead the real vehicle, instead of attempting to accurately estimate the vehicle's real position (causing small positive and negative errors seen in the plots). This strategy would provide a conservative time gap measurement, as the real vehicle would arrive at the intersection later than the estimated vehicle with the time lead term.

Sedan on Hwy52 S


Figure 25. Error plots - Sedan driven in a single lane.

Truck on Hwy52S




Figure 26. Error plots - Truck driven in a single lane.

Sedan on Hwy52 S


Figure 27. Error plots - Sedan changing lanes.

## Truck on Hwy52S




Figure 28. Error plots - Truck changing lanes.

Figure 29 shows the data plot in which the speed of the sedan from DGPS is compared to the mainline surveillance system reported speed. It can be seen that the speed accuracy for the mainline system is better than $0.326 \mathrm{~m} / \mathrm{s}(0.73 \mathrm{MPH}) \mathrm{RMS}$ if the vehicle is in the field of view of a radar sensor. Accuracy may degrade significantly should a masked vehicle accelerate or decelerate at a high rate. However, this inaccuracy will not be sustained because hard acceleration or deceleration will "unmask" the hidden vehicle, where its range and range rate will be measured accurately once it is in the field of view of the radar sensor.

In order to illustrate how the speed and longitudinal time errors affect the gap time measurement, an example is presented. Assume a vehicle is traveling $30 \mathrm{~m} / \mathrm{s}(67 \mathrm{mph})$ towards the intersection. Also assume that the surveillance system has the RMS lateral error of $0.326 \mathrm{~m} / \mathrm{s}$ ( 0.73 mph ) as measured from the sedan experiment (Figure 29) so that it measures the speed of the vehicle to be $29.674 \mathrm{~m} / \mathrm{s}$ ( 66.4 mph ) (underestimation is worst case). The gap time error (time to intersection) can be calculated at different distances from the intersection. At 500 m ( 1640 ft ) from the intersection, the real vehicle would arrive in 16.66 s while the estimated vehicle would arrive in 16.85 s for a gap time error of 183 milliseconds. At $200 \mathrm{~m}(656 \mathrm{ft})$, or about a 6 second gap), the gap time error decreases to 73 milliseconds. As the vehicle travels closer to the intersection the accuracy of the gap time measurement increases. Including the longitudinal time errors ( 48 ms RMS for the sedan experiment) presented previously, the total system gap time estimation RMS error is less than 121 ms for a sedan traveling $30 \mathrm{~m} / \mathrm{s}$ ( 67 mph ) 200 m ( 656 ft ) from the intersection. This error is small considering human reaction time and vehicle dynamic time constants. The estimation algorithm could account for these errors by conservatively estimating the vehicle 121 ms in the future, thus eliminating possible late DII triggering due to measurement and estimation error.


Figure 29. Speed error for the sedan.
In order to test the robustness of the mainline system to a single sensor failure, one of the radar sensors was shut down and the same experiment described above was performed. It was found from this experiment, that this did not adversely affect the accuracy of the system (see Figure 30) and only in some cases, did the errors grow slightly in the region covered by the concerned radar unit. This provides strong evidence that losing a single sensor does not significantly degrade the performance of the main line system. Since the system monitors its own health, sensor failures can be addressed while the system is still running. This test also illustrates that it may be possible in future installations to use fewer radar units spaced further apart and thus reduce the infrastructure costs.

Sedan on Hwy52S


Figure 30. Sedan driven in a single lane with one radar shut down.

## Remaining Questions

Motorcycle Radar Cross Section Resolution. Complete tests need to be conducted to ensure that motorcycles are consistently detected by mainline sesnors and are not lost in the radar cross section of other vehicles following closely behind. The motorcycle radar cross section will be lost in the radar cross section of a large semi-truck at small separation distances. To ensure the safety of both the motorcyclist and the driver waiting at the minor road, the mainline surveillance system must be able to resolve (and detect) a motorcycle traveling in front of a semi-tractor while separated by relatively small distances. Experiments were conducted (and documented herein) to determine the distance at which the radar cross section of a motorcycle will be lost in the radar cross section of a heavy truck.

Motorcycle testing was performed in September 2005. In this test, a modern motorcycle (a 1978 BMW R80/7) was equipped with a Trimble MS750 GPS receiver and a wireless modem used to receive DGPS corrections. The MS750 and associated hardware was installed in the left-side hard luggage (see Figure 31). The motorcycle traveled at speeds between 46 and $54 \mathrm{mph}(21-24 \mathrm{~m} / \mathrm{s})$, with the heavy truck following at distances between 85 ft and $196 \mathrm{ft}(20 \mathrm{~m}-60 \mathrm{~m})$. This produced headways in the range of 0.95 to 2.5 seconds. (A 20 -meter ( 66 ft ) headway at $24 \mathrm{~m} / \mathrm{s}$ ( 54 mph ) speed was uncomfortably close.)

Figure 32 shows the results of the testing at the Minnesota Test intersection. At close following distances (20-35 meters, (66-115 ft)), the radar is able to distinguish the motorcycle from the heavy truck approximately $50 \%$ of the time. Moving to larger headways, the ability of the radar to distinguish between the motorcycle and the heavy truck improves considerably. Between 35 and 50 meters, the radar distinguishes the two vehicles $75 \%$ of the time; at headways greater than 50 meters (approximately 2 second headway), the radar detects both vehicles approximately $95 \%$ of the time. This detection rate is sufficient for the mainline surveillance system.


Figure 31. Motorcycle used to determine distance at which radar cross-section is lost in heavy truck cross-section.
Real-time motorcycle position and speed data is delivered to the data acquisition system in the truck via the data broadcast antenna. Time synchronization data is delivered to the motorcycle computer from the truck computer also via the data broadcast antenna.


Figure 32. Results of motorcycle-heavy truck radar signature study. Speeds of 46 to 54 MPH ( $21-24 \mathrm{~m} / \mathrm{s}$ ) were used to determine the separation distance at which the radar cross section of the motorcycle is lost in the radar cross section of the heavy truck. The plot above shows that at separation distances of more than 35 meters, the radar is able to distinguish between the two vehicles more than $75 \%$ of the time. This detection rate is sufficient for the mainline surveillance system.

## Chapter 4: <br> Minor Road Surveillance Subsystem

### 4.1 Objectives

The objectives of the minor road surveillance subsystem are twofold. First is to allow DII activation only if a vehicle is present on the minor road. Second is to determine the classification (via vehicle size and shape) of the vehicle waiting at the minor road. For driver behavior characterization, this classification allows the correlation of gap selection with vehicle type. For a deployed IDS system, knowledge of vehicle class allows DII timing to better match vehicle dynamic capability, facilitating warnings likely to be accepted by drivers.

As was the case for the mainline sensors, cost is a critical concern.

### 4.2 Requirements

### 4.2.1 Presence detection

A robust means to detect the presence as well as absence of vehicles at the minor road stop sign is needed for two reasons. First, distraction of drivers on the mainline can be minimized if the DII is triggered only if a vehicle is waiting on the mainline. Second, the system must provide a warning (when appropriate) to all vehicles on the minor road. If vehicle presence is missed, the driver fails to benefit from the IDS system.

### 4.2.2 Vehicle classification capability

Vehicle mass and size dictate the dynamic performance envelope of highway vehicles. To properly time warnings to drivers of various types of vehicles, the IDS system may require information regarding the dynamic capability of the vehicle attempting to enter or cross the traffic stream. As of February 2005, the following classification granularity is operational: motorcycle/passenger car, SUV/Light Truck, Medium Duty Truck/School Bus, Heavy Duty. The performance of the system is described in the performance specification section of this report.

### 4.2.3 Subsystem coverage

The minor road surveillance system must provide coverage for all types of vehicles legally able to use the road. In Minnesota, the maximum legal length for any vehicle is 23m ( 75 ft ) (a semi-tractor pulling two trailers). Maximum height is 4 m ( 13.5 ft ) without special permit. This defines the minimum coverage area for the vehicle classification system.

### 4.2.4 Insensitivity to vehicle design variations

The minor road surveillance subsystem should be insensitive to variations in vehicle designs and design parameters. The subsystem should not be adversely affected by vehicle color, window tint, body panel curvature, chrome, "spinner" wheels, etc.

### 4.2.5 Bias in errors

The vehicle classification system errors should be biased so that misclassifications results in the identification of a vehicle in the next larger class. This will result in conservative DII alert and warning timings, maintaining system safety margins.

### 4.3 Constraints

As part of this design, Mn/DOT did place a few constraints on the system. These constraints are enumerated below.

### 4.3.1 Proximity to Highway

No sensor shall me mounted closer than 12 feet to the road shoulder.

### 4.3.2 Low Voltage

Any sensor located in the clear zone (the clear zone is defined as any location within 30 feet of the road shoulder) must be supplied with direct current less than 15 volts.

### 4.3.3 Break Away

All fixtures must meet federal and state breakaway standards. All electrical equipment located in the clear zone must be equipped with breakaway electrical connectors.

### 4.3.4 Restriction in Median

No equipment shall be located in the median of the expressway. This is primarily due to the need to perform rapid maintenance operations in the median.

### 4.4 System Components

The minor road surveillance subsystem consists of three primary capabilities: sensing, communications, and computation. A wide variety of candidate sensors that can provide presence and vehicle classification information are available. Candidate sensors are described below, with the choice of laser scanners justified.

Because the choice of sensor has a significant impact on the design of the surveillance system, a survey of sensors and the rationale for choosing laser scanners is describe in section 2.4.1 below. Communication and computation are subsequently discussed in section 2.4.2.

### 4.4.1Sensors

A number of candidate sensors (and sensing systems) are available for performing vehicle classification. Each of the candidate sensors is described below in terms of advantages and disadvantages, from both sensor performance perspectives and operational characteristics.

There are many off the shelf sensors that can perform vehicles classification. However, most of these systems are turn-key and do not provide raw sensor data. It was desirable to find sensors that could be used in a classification system and to build it in house. Once the surveillance system accuracy is documented, it can be used to test off the shelf systems. Furthermore, it was important to use the classification sensors simultaneously track vehicles on the minor road to reduce system cost.

### 4.4.1.1 Imaging/Cameras

Both visible light and infrared cameras were considered for a potential vehicle classification system. Visible light cameras are relatively inexpensive, although imageprocessing equipment needed to analyze captured images can be fairly expensive. However, the performance of visible light cameras suffers greatly with changes in lighting and weather (i.e., precipitation and fog) conditions. Furthermore, avoidance of the distortion associated with wide-angle lenses requires that a camera be mounted away from the intersection, complicating the system design and construction features.

Infrared/thermal imaging cameras were also investigated. A primary advantage to these cameras is insensitivity to weather conditions; precipitation has little adverse effect on the system performance. However, because of a lack of consistent large thermal gradients between the outer surface of a vehicle and the atmosphere, acquisition of vehicle height profile data is difficult, resulting in low classification accuracy rates.

Visible light cameras were used to document the performance of the vehicle classification system. The approach used was to capture images of vehicles in the field of view of the classification system; these images were time synchronized with the classification system data. Data was post-processed whereby a human reviewed a captured image and classified the vehicle in the image into one of nine classes. The human data served as the reference against which the classification system data were measured.

### 4.4.1.2 Radar Sensors

Radar was also considered for a vehicle classification system. Eaton Vorad produces a "tollgate" version of the EVT-300, which was designed to help toll road operators match
collected tolls with estimated tolls, where the toll estimation was based on measured vehicle class. Initial discussions with Eaton marketing indicated that the sensor would estimate a vehicle size based on vehicle radar cross section. However, subsequent discussions revealed that the tollgate sensor provides the same information (range, range rate, and azimuth) as the standard EVT-300. The difference between the tollgate and standard sensor is that the tollgate sensor is optimized for low speed vehicles (sensitivity from 0.4 to $32 \mathrm{kph}(0.25$ to 20 mph$)$ ). Moreover, the lack of overhead sensor mounting opportunities makes optimal sensor positioning and aiming difficult. Additional sensor data and subsequent fusion is needed to implement an Eaton tollgate sensor-based vehicle classification system.

### 4.4.1.3 Loop detectors

Loop detectors are typically used to detect vehicles and to determine queue lengths at signalized intersections. Loop detectors function by sensing a change in inductance, which occurs when an electrically conductive mass is placed over the energized loop. The reliability, cost, installation, electrical interface requirements, and performance of loop detectors for presence sensing are well documented.

Advanced signal processing techniques have been used to enhance the capability of the standard loop detector. The change in inductance exhibited by an in-pavement loop is proportional to the electrically conductive mass of the vehicle over the loop, and inversely proportional to the distance from the loop centroid to the center of the electrically conductive mass of the vehicle overhead. Discussions with 3M, a major supplier of in-pavement loop detector modules, indicate that the best vehicle classification performance offered by an in-pavement based system, either loops or microloops, would be approximately $70 \%$. This is insufficient for this application; drivers demand properly timed warnings at a frequency greater than 2 of 3.

Developments in vehicle classification by loop detectors will continue to be monitored; if performance gains are sufficient and if funds are available, a loop-based system will be installed at the test intersection.

### 4.4.1.4 Scanning Laser Sensors

A third alternative to vehicle classification uses a vertically aligned laser scanner to determine the vertical profile of a vehicle. This data combined with vehicle position data from radar or a horizontally aligned laser scanner can be used to determine the length of the vehicle. The fusion of this data provides a "snapshot" of the side of the vehicle, allowing it to be classified into one of four categories.

This dual laser approach to vehicle classification requires a significant investment. The Minnesota system uses Sick LMS 220 industrial laser scanners. This laser sensor carries a cost of approximately $\$ 6,500$; high speed communication boards add $\$ 500$ to that price. The sensors are straightforward to mount, and sensors communicate via RS422. It should
be noted that 2 pairs of sensors are needed to serve a four leg rural intersection. The pair of sensors act as both a classification system and a presence detector.

In the following, the design and performance of the laser based vehicle classification system is provided. Also discussed is the use of height alone to classify vehicles (would save $\$ 7,000$ per minor road leg) or the fusion of Eaton Vorad Tollgate sensor data with height data from the Sick scanner (saving $\$ 6000$ per minor road leg).

### 4.4.2 As Built Description of the Minor Road Surveillance System

### 4.4.2.1 Architecture and data flow

### 4.4.2.1.1 Sensor Layout

Two primary sensors were used for the minor road surveillance system: scanning lasers and radar. Because of its long range, radar was aimed along the approach of the minor road, and was used to detect vehicles approaching the intersection.

Radar provides vehicle range, range rate, and azimuth information. However, it is unable to provide information regarding the classification of vehicles. Two laser scanners, one horizontally aligned and one vertically aligned were used to capture the length and height of vehicles on the minor road waiting to enter or cross the mainline traffic. This length and height information was used to classify vehicles based on the area they displace as viewed from the side.

Figure 33 shows the sensor placement for CSAH 9E and CSAH 9W sections. The system consists of one EVT-300 radar unit facing the traffic on each of the two sections of road (R15, R16). The radar detects when a vehicle is likely to enter the area surrounding the stop bar. A horizontally mounted SICK LMS221 sensor is used to track (and classify) slow-moving/stopped traffic at the intersection. The lidar data processing software identifies vehicles from a cluster analysis of the returned laser readings. The horizontally mounted laser sensor is also used to measure the trajectory of the vehicles as they leave the minor road and enter or cross the mainline.

The vehicle classification system also uses a vertically mounted SICK LMS221 sensor (S1, S4) that measures the height profile of the vehicle passing by it. With the location of the vehicle known from measurements provided by the horizontal laser scanner, the length of the vehicle passing by can be determined. The measured length and height of the vehicle are used to compute the area of the vehicle (from the side) stopped on the minor road; as will be demonstrated. Area can be correlated with vehicle class to offer a high fidelity vehicle classification.


Figure 33. Sensor Coverage along minor road at the Hwy52 intersection.

### 4.4.2.1.2 Sensor Mounting

The radar antenna was attached to a mount that allows the antenna pitch and yaw angles to be changed as needed. The same radar mount used for the mainline sensors was used on the minor road. After mounting, the sensor was aimed and calibrated (procedure described under the 'Mainline Implementation' section).

A similar mount is used to mount the lidar sensors to the flanged channel (Figure 34). The sensor mounting plate has square holes that are used to attach the plate to the sensor and hence the same mount can be used to attach the sensors vertically and horizontally.


Figure 34. Lidar sensor mount assembly.

### 4.4.2.1.3 Communication

Sensor Station Hardware. The sensor station layout is similar to that for the mainline. Each sensor is connected to a data processing computer in a separate cabinet. While the radar antenna and the lidar sensor can be placed close to the road ( 12 ft from the road shoulder), the actual processing hardware is kept outside the $\mathrm{Mn} / \mathrm{DOT}$ specified clear zone ( 30 ft from the road shoulder). Power and data communication to the radar antenna and lidar sensor is provided by cable run in a conduit underground.

The hardware for the radar antenna is the same as that for the mainline. For the lidar sensor an additional power supply is necessary and a high-speed data card is used in the processing computer. This computer runs the radar and lidar sensor drivers and then converts the range and range-rate data provided by the sensor into state-plane coordinates used by the vehicle tracking system. This data is sent via Ethernet to the main processing computer located at the main controller cabinet. Because of the distance from the processing computer to the main cabinet, a VDSL modem is used in the sensor cabinet and the main controller cabinet to amplify and demodulate the Ethernet signals, respectively.

The main cabinet contains hardware to collect all the VDSL lines from all the minor road sensor stations. The sensor station hardware layout is shown in Figure 35. Each leg of the minor road has two sensor stations that each have a lidar unit (one mounted vertically and one mounted horizontally). Since there is a need for only one radar antenna in the section, one of these stations will also host the radar.


Figure 35. Sensor Station Hardware.

Figure 36 shows the overall dataflow diagram for all the minor road sensors. Each sensor receives time synchronization signals from the timeserver and this is used to timestamp the pre-processed radar sensor data. The details of the processing are discussed in the next section.


Figure 36. Minor Road Communication Dataflow Diagram.

### 4.4.2.1.4 Processing

### 4.4.2.1.4.1Local Processing at the Detection Sensor Station

Pre-processing of the raw sensor data is done within each sensor station. Figure 37 shows the dataflow between various processes in the sensor station. Each sensor station currently can handle up to four radar sensors and two lidar sensors. Each sensor unit has a driver process that initializes the sensor and reads its raw data.


Figure 37. Detection Sensor Station Dataflow.
Each data set is time-stamped before being transmitted to the main controller; this allows the vehicle-tracking module in the main controller to account for all the lags in the data transit process. An NTP client running in the background ensures that the sensor station clock and the main controller clock are synchronized.

The raw radar data is converted to state plane coordinates using the sensor position and yaw angle with respect to state plane coordinates (See 'Mainline Processing' section). The raw lidar data needs further processing before a target position can be extracted. The procedure for vehicle coordinate extraction is similar to that described by Sergi [11], with a few modifications for the roadside sensor case.

The SICK LMS221 sensor communicates with the controller card through a high-speed RS485 card that allows communication at 500kBaud. The sensor has range of 30m (98 ft ), and a field of view of 180 degrees with a resolution of 0.5 degrees. The range
resolution of the senor is 1 cm and an estimated error of $+/-6 \mathrm{~cm}$ [11]. At these settings, the sensor transfers data to the controller computer at approximately 35 Hz .

The raw data from the sensor is a set of range measurements for each scan (361 points) and these data points are grouped into clusters [Sergi et al, 11]. While Sergi performs pattern matching for the clusters to find vehicles, the method here uses the cluster statistics (cluster size, length, etc.) to determine the position of vehicles. Sergi's method can more accurately determine the exact position of the front/back of the vehicle depending upon its location with respect to the sensor, but this approach only works well for vehicles of a particular height because the sensor's field of view is on a single plane. Since the ground clearance of all the vehicles that will be detected at a rural intersection vary significantly, no optimum sensor height is possible to accurately determine the position for all types of vehicles. The additional processing done to determine the front/back of the vehicle hence is not effective for this application.

Figure 38 shows how the lidar sensor can accurately determine the vehicle position if it is placed at the correct height. The lidar data points are grouped into clusters that have parameters such as number of points, cluster length, cluster start and end point, etc. It is then possible to fit lines to the points in the clusters and hence determine the location of the front of the vehicle as described by Sergi.

While the example dataset in Figure 38 illustrates ideal conditions, it can be easily seen why this will not work for a taller vehicle with higher ground clearance.

Figure 39 shows the data set when the lidar sensor beam hits the vehicle lower down only hitting the tires. Two clusters are found representing the tires of the vehicle and since no perpendicular front surface is found, none of the clusters can be used to find the front of the vehicle. For this situation, the lidar filter was modified to not look for vehicle bumpers and reports both clusters as valid targets. It leaves it to the vehicle-tracking module in the main controller to determine whether there are two targets or one. Since the vehicle-tracking module has previous knowledge (from radar aimed at minor road) of the target approaching the lidar sensor, it can correctly associate the clusters to the vehicle. This method compromises lateral and longitudinal lane position accuracy, but this error is usually quite small ( $<1 \mathrm{~m}$ laterally and $<3 \mathrm{~m}$ longitudinally).

The vehicle position data is converted from local coordinates to state plane coordinates using the sensor position and yaw angle with respect to the state plane coordinates before it is sent to the main controller.


Figure 38. Optimal Lidar Height.
The front and side of the vehicle can be clearly detected.


Figure 39. Non-Optimal Lidar Height.
On vehicles with high ground clearance, only the tires can be detected.

### 4.4.2.1.4.2 Local Processing at the Classification Sensor Station

The classification sensor station uses a vertically mounted lidar sensor that measures vehicle height profiles as a vehicle passes. Figure 40 shows the dataflow between various processes in the sensor station. Each sensor station currently can handle up to two lidar sensors. Each sensor unit has a driver process that initializes the sensor and reads its raw data.


Figure 40. Detection Sensor Station Dataflow.

The lidar sensor information is used to determine the maximum height of the vehicle that passes by it, as well as the exact time the vehicle's front and rear bumper traversed the sensor beam (See Figure 41). This information is sent to the vehicle-tracker in the main controller which determines which previously know target went past the sensor. With knowledge of the target's speed and position, the length of the vehicle is calculated.

Each data set is time stamped before being transmitted to the main controller which allows the vehicle-tracking module in the main controller to account for all the lags in the data transit process. An NTP client running in the background ensures that the sensor station clock and the main controller clock are synchronized.


Figure 41. Vertically Placed Lidar to measure vehicle profile.

### 4.4.2.1.4.3 Central Processing

A central process in the main controller gathers all the data from every sensor on the minor road and groups it before sending the data to the vehicle-tracking module. This process also checks to see if the sensor is functional and reports the sensor status. Figure 42 shows the data flow for the sensor collector process. The same process is used to gather data from the other sensors on the mainline as well as the crossroads. The details of data collection from these sensors are discussed in their respective sections. This process does not handle the vehicle classification data. This data is directly sent to the vehicle-tracking module where it is used to assign heights and lengths to known targets.


Figure 42. Sensor Collector Process at the Main Controller (Minor Road Sensors).
Vehicle-Tracking. For the minor road, the vehicle-tracking module must be able to detect and track stopped vehicles at the intersection of the minor road and the mainline, and determine the type of maneuver they make as they leave the intersection. As the vehicle moves through the system, the regions in which the vehicle is located must also be determined to ease the post-data processing.

Functional requirements for the tracking module include:

1. Continuous tracking and estimation of the state of all vehicles in the system
2. Assignment of unique Identification numbers to every vehicle in the system. The ID must be maintained for that vehicle as long as the vehicle is being tracked by the system, even if the target changes lanes or makes a turn.
3. Provision of vehicle position (Lane number as well as location in the lane)
4. Assignment of a region of travel for every target (to ease the post-dataprocessing).

Sensor Data Pre-Filtering. The tracker reads the collected sensor data, applies a filter, and then uses it for tracking purposes. Before any of the sensor data is used for state estimation, it is filtered to remove irrelevant data (See Figure 43). The first filter removes irrelevant targets based on target heading. Sensor data from vehicles heading toward or leaving the intersection are accepted; all other data are discarded. This reduces the chance that false targets are tracked by the system.

The second filter ensures that valid targets are located on the road. This filter compares the location of identified targets with the landscape local to the sensor. The landscape is represented by a geospatial database [8, 9], which describes the geometry of the roadway and locates other hard elements within the boundaries of the intersection. The geospatial database contains location and attribute information about lane-centers, lane-boundaries, road-islands, road-shoulders, guardrails, etc. The database information is provided through a server process that responds to application driven requests for data. Upon initialization, this filter module requests lane center information for all intersection lanes, and converts this to its own format to be used to filter targets outside the lanes. If the sensors detect a target to be within $2 \mathrm{~m}(6.5 \mathrm{ft})$ of the lane-center, it is considered to be in that lane; if it is outside this threshold, it is either in the adjacent lane or on the shoulder. A larger threshold is required for vehicles on the minor road since a stopped vehicle at the intersection is not usually in the center of the lane. Vehicles waiting to turn right onto the mainline tend to wait on the road shoulder, while vehicles waiting to go straight through tend to be more in the lane.

After the data has been filtered, a reduced set of valid targets is obtained ( $n$ unfiltered targets are reduced to $m$ targets as shown in Figure 43). Since each sensor acts independently, target information is not provided at the exact same time. This creates a time lag, and compensation must be made to bring up to date and synchronize the data to the current time. This time lag is the time difference from when the sensor last detected a target plus transmission time, and is estimated by measuring the time difference between the update step (time at that moment) and the sensor-station timestamp for that sensor measurement. Typically measured lag is found to be less than 60 ms .

Using past vehicle state data (position and velocity), the new vehicle state is calculated by projecting ahead using the calculated time lag for each target. The resultant table contains an estimate of the measurements at the current time step. This data is then used in determining the minor road system state at the current time step.


Figure 43. Pre-Filtering and projection of sensor data.

Vehicle-Tracking and Classification/State Estimation. Every target in the minor-road system goes through three steps as described in the mainline processing section (section 0 in Chapter 2 on page 30):

## 1. New Target Detection

2. Target Tracking

## 3. Target Release

The vehicle-tracking process also receives information from the lidar classification station when a vehicle passes by the sensor. Figure 44 illustrates the inclusion of this information into the Known Targets Table. The vertical lidar sensor information is used to determine the maximum height of the vehicle that passes by it, as well as the precise time the vehicle's front and rear edges move past the sensor (See Figure 41). Since, the position on the road of the sensor beam is known, a search for a target near this region is made to associate the classification information. Using the target's current state information, the vehicle-tracker determines the length of the vehicle. The height and length parameters are used to classify vehicles by type as described in section 0 .


Figure 44. State Estimator Data Flow.

### 4.4.2.2 Implementation

### 4.4.2.2.1 Sensor Mounting

Once the radar and lidar sensor mount is attached to the flanged channel (Figure 45), the antenna is then aimed and calibrated. The aiming procedure for the radar has been previously described in the mainline section. A similar procedure is followed to aim the horizontal lidar sensor.


Figure 45. Radar antenna and Lidar Sensor (Horizontal) mounted on flanged channel.

For the vertical lidar sensor (Figure 46), it is sufficient if the sensor is roughly aimed to be perpendicular to the road in front of it because the software self-calibrates by detecting the road.


Figure 46. Lidar Sensor (Vertical) mounted on flanged channel.

### 4.4.2.2.2 System Performance

### 4.4.2.2.2.1 Classification System Performance

To establish a correlation between a vehicle's maximum height and length with the type of vehicle, an experiment was performed that captured the height and length data along with an image of the target being classified.

Figure 47 shows the data flow for the experiment. The retro-reflective sensor setup used for the mainline experiment was used here to trigger a camera to take a picture every time a vehicle went past the lidar sensor (Figure 48 and Figure 49). These images were inspected by a human to determine the type of the vehicle in the image. As can be seen in the results discussed below, the analysis of the data showed that it was possible to establish a correlation between the type of vehicle and the maximum height and length of the vehicle.


Figure 47. Vehicle Classification Experiment Dataflow Diagram.


Figure 48. Vehicle Classification Experiment Components.


Figure 49. Vehicle Classification Experiment Schematic.

Vehicle classification data, as well as the target images were collected over a period of a day. When a target passed in front of the retro-reflective sensor a time-stamped image of the target was captured. This timestamp was used to query the target state database for a target present within the search zone shown in Figure 49. Once a vehicle was confirmed to be detected within the search zone, the human operator was shown an image of the vehicle and was asked to choose the type of vehicle (See Figure 50). Nine different categories were selected for the classification as shown in Figure 50. An analysis of the vehicle types as judged by the human operator, combined with the height and length information retrieved from the sensors was used to arrive with a vehicle classification scheme.


Figure 50. Vehicle Classification Analysis by a human operator.
Figure 51 and Figure 52 show a histogram plot of the heights and lengths data collected during the experiment. As can be noted from the plots, using only one of the parameters is not sufficient to accurately determine the type of vehicle. For this purpose, equations were developed to use both the height and the length of the targets and hence separate the vehicle types. Figure 53 shows a histogram plot using a combination of the two parameters and it can be seen that the vehicles can be separated into four broad categories:

1. Motorcycles, sedans and small SUVs,
2. Large SUVs and pickup trucks,
3. Mid-sized trucks, and
4. Semi-trucks and other large vehicles


Figure 51. Vehicle Height Histogram (122 Vehicles).


Figure 52. Vehicle Length Histogram (122 Vehicles).


Figure 53. Consolidated Histogram of Vehicle Height and Length (122 Vehicles).

### 4.4.2.2.2.2 Minor Road Vehicle Tracking System Performance

A similar experiment to the one conducted on the mainline was performed on the minor road to determine the minor road vehicle tracking system performance. Two probe vehicles fitted with high-accuracy DGPS systems were driven along the minor road. The probe vehicles made right-turn and straight-through maneuvers at the intersection. To determine the accuracy of the minor road tracking system, the time that the probe vehicles actually left the minor road was compared to the time the vehicle state estimator indicated the target left the minor road. This accuracy is critical as the actual time a vehicle leaves the minor road is used to determine the gap that the vehicle selected when making its maneuver. Figure 54 shows the dataflow for the experiment.


Figure 54. Minor Road Performance Experiment Dataflow.
The results of two of the experimental runs using a sedan as a probe vehicle are shown in Figure 55 and Figure 56. The plots illustrate the errors for the section when the sedan leaves the minor road. The average longitudinal time error for all the experimental runs for the straight through maneuver was found to be -276 ms . The average longitudinal time error for right turns was found to be -146 ms . These errors are minimal and do not significantly affect the measurement of the gaps selected by vehicles making these maneuvers.


Figure 55. Errors with a sedan - Straight through maneuver.


Figure 56. Errors with a sedan - Right turn maneuver.

## Chapter 5: <br> Crossroads (Median) Surveillance Subsystem

### 5.1 Objectives

The primary objective of the crossroads (median) surveillance subsystem is to provide an observational record of driver behavior in the median of a rural expressway. Two questions will be answered:

What is the percentage of drivers that execute a left turn or straight crossing in one step?
What gaps are selected by drivers in the median, and how does gap selection change as a function of the time a driver has waited in the median (i.e., will drivers accept smaller gaps as their time waiting increases)?

Answers to these questions are needed to develop an effective driver interface. For instance, crash analysis has shown that most rural expressway thru-Stop intersection crashes occur on the "far" side of the intersection, and are thus associated with the passage through the median. Clearly, driver behavior will impose a significant influence on the design of an effective DII.

### 5.2 Requirements

### 5.2.1 Coverage area

The entire median area of the cross roads must be covered by the crossroads surveillance system.

### 5.2.2 Accuracy

The primary concern with the crossroads area is not the absolute position of the vehicle within the crossroads, but rather with precise measurements of the times at which a vehicle enters and leaves the intersection, respectively. Gap definitions depend upon the time a vehicle leaves a particular area; consistent measurements dictate that the system accurately measure that time.

### 5.3 Constraints

As part of this design, Mn/DOT did place a few constraints on the system. These constraints are enumerated below.

### 5.3.1 Proximity to Highway

No sensor shall me mounted closer than 12 feet to the road shoulder.

### 5.3.2 Low Voltage

Any sensor located in the clear zone (the clear zone is defined as any location within 30 feet of the road shoulder) must be supplied with direct current less than 15 volts.

### 5.3.3 Break Away

All fixtures must meet federal and state breakaway standards. All electrical equipment located in the clear zone must be equipped with breakaway electrical connectors.

### 5.3.4 Restriction in Median

No equipment shall be located in the median of the expressway. In this application, this constraint is motivated for three reasons. First, equipment located in the median or near the crossroads can potentially block sight lines of vehicles in the median. For obvious reasons, this is discouraged. Second, because of the need to quickly clear medians during snow events, equipment located near the roadway is susceptible to damage caused by snowplow wing blades. Third, intersection crashes often result in vehicles coming to rest in the crossroads median. Equipment located in the median is usually damaged or destroyed by an intersection crash.

### 5.4 System Components

The crossroads surveillance subsystem consists of three primary capabilities: sensing, communications, and computation. A wide variety of candidate sensors which can track vehicle in the crossroads are available. Candidate sensors are described below, with the choice of sensors used at the intersection explained.

Because the choice of sensor has a significant impact on the design of the surveillance system, a survey of sensors and the rationale for cameras is describe below. Communication and computation subsystem descriptions follow.

### 5.4.1 Sensors

Although not a component of the IDS system that will be deployed, the behavior (i.e., trajectory) of drivers as they pass through the intersection crossroads is computed and stored by the Minnesota system as a means to collect baseline data. At the Minnesota Test Intersection, the crossroads area is relatively small ( $15.25 \mathrm{~m} \times 30.5 \mathrm{~m}$ ( $50 \mathrm{ft} \times 100 \mathrm{ft}$ )), and vehicles generally move at low speeds (typically 8-16 kph (5-10 mph), with a maximum speed of $32 \mathrm{kph}(20 \mathrm{mph})$ ).

This crossroad area at the test intersection is typical for rural expressway thru-Stop intersections. Low expected vehicle speeds, combined with the small area of coverage resulted in a broad choice of candidate sensors.

### 5.4.1.1 Laser scanners

The original plan was to use laser scanners to track vehicles passing through the crossroads. A pair of Sick LMS 221 sensors mounted on opposite sides of the intersection would have provided sufficient coverage of the median area. When $\mathrm{Mn} /$ DOT was presented this design option, constraints on use of the median eliminated the laser scanner as a sensor choice.

### 5.4.1.2 Visible light cameras

For daylight operations, visible light cameras offer a viable option for crossroads surveillance. Visible light cameras are relatively inexpensive, offer high resolution, offer a wide variety of lenses and filters, and are used by a majority of DOTs, thereby offering a comfort factor. However, in low light and night operation, visible light cameras fail to produce images of sufficient contrast, thereby rendering accurate vehicle trajectory tracking impossible during those conditions. Alone, a visible light camera is unlikely to meet surveillance system performance needs. However, a visible light camera will capture crash events, leading to crash reconstruction and a better understanding of the conditions that led to the crash.

For evaluation purposes, a visible light camera was procured and tested as a crossroads surveillance sensor; the specifications of the chosen camera are provided below:

Camera Model: Panasonic WV-BP330
Picture Element: 1/3" CCD
Resolution: 768 (H) x 494 (V) pixels
SNR: 50 dB
Lens mount: C or CS
Lens Model: Rainbow CCTV L212VDC4P
Focal length: $2.7-12 \mathrm{~mm}$
Max. Aperture: 1.4
Field of view: $83 \times 67$ degrees at 2.7 mm 23 x 17degrees at 12 mm
Mount: CS
Augmentation of visible light cameras with an infrared illumination source may improve the ability with which a vehicle in the crossroads can be identified and tracked. Recently introduced Super Dynamic Range Cameras (SDRC) provide, with electronic enhancement, sensitivity up to 32 times greater than that of standard CCD cameras. When combined with a near-infrared light source, these cameras can also be used for near-infrared (B/W) surveillance in settings with no visible light.

Camera Model: Panasonic WV-CL920A
Picture Element: 1/2" CCD
Resolution: 480 lines horizontal (color mode) / 570 lines horizontal (B/W mode)
SNR: 50 dB
Minimum Illumination: 0.14 lux ( 0.014 fc ) at F1.4 (Color Mode); 0.01 lux ( 0.001
fc) at F1.4 (B/W Mode)
Lens mount: C or CS

Lens Model: Rainbow Model:L612VDC4P
Focal length: 6-12 mm
Max. Aperture: 1.4
Field of view: $56.1^{\circ} \times 43.6^{\circ}$ at 6 mm
$29.9^{\circ} \times 22.6^{\circ}$ at 12 mm
These two cameras were installed at the Minnesota Test intersection both to collect driver behavior data and to collect comparative sensor data. The baseline system (WV-BP330 camera with lens) represents a $\$ 600$ investment; the augmented SDRC camera system (including illuminator) represents a $\$ 3000$ investment. Clearly, the SDRC camera with augmented illumination will provide excellent video performance during the evening hours. It was however found that the illumination provided was still insufficient for vehicle detection at night.

### 5.4.1.3 Infrared / Thermal Imaging cameras

IR cameras are quite disparate in terms of performance, cost, support, and availability. After reviewing product specifications and convincing suppliers to provide demo units, three IR cameras were selected for a "shootout." In this analysis, securing a camera with the highest performance:cost ratio was the primary objective.

The specification most influencing the performance:cost issue was the camera resolution. Of the IR camera distributors willing to provide demo units, two resolution categories were available: $320 \times 240$ pixels, and $160 \times 120$ pixels. The higher resolution camera costs approximately twice that of the lower resolution camera. The performance:cost issue would be answered by determining whether a high resolution camera with a wide field of view would offer better performance than two lower resolution cameras, each with a narrow field of view lens.

The three candidate IR/thermal imaging cameras are described below.
FLIR A40V: This camera offers $320 \times 240$ resolution, and a wide variety of available lenses, with fields of view ranging as shown below

## Field of view

$24^{\circ}$ Standard: $24^{\circ} \times 18^{\circ}$
$7^{\circ}$ Telescope: $7^{\circ} \times 5.3^{\circ}$
$12^{\circ}$ Telescope: $12^{\circ} \times 9$
$45^{\circ}$ Wide angle: $45^{\circ} \times 34^{\circ}$
$80^{\circ}$ Wide angle: $80^{\circ} \mathrm{X} 60^{\circ}$
Other specifications can be found at http://www.flirthermography.com/cameras/camera/1042/
The camera cost without lens is approximately $\$ 15,000$. One advantage to the A40V over the other cameras evaluated is that the A40V uses interchangeable lenses. The 45-degree FOV lens carries a price of approximately $\$ 5,000$; the 80 -degree FOV lens cost is approximately $\$ 8,000$.

FLIR A20V: The FLIR A20V offers a resolution of $160 \times 120$ pixels, or $11 / 4$ the resolution of the FLIR A20V. The camera cost is approximately $\$ 10,000$; that cost includes the price of the lens. It is important to note, however, that the camera comes with a fixed lens, and a change of field of view requires a new camera. The selection of lenses available for the A20V is also more limited than those available for the A40V.

## Field of view

$25^{\circ}$ Standard: $25^{\circ} \times 19^{\circ}$
$12^{\circ}$ Telescope: $12^{\circ} \times 9^{\circ}$
$45^{\circ}$ Wide angle $45^{\circ} \times 34^{\circ}$
Other specifications can be found at http://www.flirthermography.com/cameras/camera/1031/
Indigo Omega: The Indigo Omega also offers resolution of $160 \times 120$ pixels in a significantly smaller package than the FLIR A20. Indigo systems was purchased recently by FLIR systems, and the sensor has since been renamed the A10. The range of lenses available for the A10 are:

## Fields of view

$25^{\circ}$ Standard: $25^{\circ} \times 19^{\circ}$
$15^{\circ}$ Telescope: $15^{\circ} \times 11^{\circ}$
$40^{\circ}$ Wide angle $40^{\circ} \times 30^{\circ}$

Other specifications can be found at http://www.flirthermography.com/cameras/camera/1043/
Figure 57 shows images from the three infrared cameras that were evaluated. From the comparison of the three images, it can be clearly seen that the A40 camera has the highest resolution and clarity. The A20 and Omega cameras have the same resolution, but the image from the A20 is sharper.

The Omega camera is extremely small, but doesn't offer the sharpness of the A20V. Because size is not an issue for a mast-mounted camera, the size advantage is offset by relatively poor image quality.


Figure 57. Images from the three infrared cameras evaluated.

### 5.4.1.4 Loop Detectors

Loop detectors were also considered as a means to indicate the times at which vehicles entered and vacated the crossroads area. Loop detectors are attractive because they represent a proven technology; DOTs have a great deal of experience with them, and they are relatively inexpensive to install in the pavement. However, to their detriment, loop detectors provide a measure of presence only, making trajectory tracking and crash reconstruction difficult. Installation of loop detectors in the median would also require pushing additional conduit and cabling underneath the mainline, and installing hand holes in the median.

### 5.4.1.5 Radar

Eaton Vorad Tollgate sensors were also considered for crossroads sensors. The Tollgate sensor offers low speed sensitivity and sufficient range to sense the state of the crossroads. The relatively narrow horizontal sweep of the radar sensor requires that the sensor be located outside of the crossroads area if the full median area is to be covered by the radar field of view.

Location of the sensors away from the intersection median results in the situation where mainline traffic blocks the view of the median by the sensor. This works to lessen system reliability by increasing the opportunities to either miss targets or misclassify mainline vehicles for vehicles in the median.

### 5.5 As Built Description of the Crossroad System

### 5.5.1 Sensor Placement and Image Acquisition

With constraints and requirements considered, video sensors were the obvious choice for the crossroads surveillance system. There are four cameras used for vehicle detection at the cross roads of the intersection as shown in Figure 58. Two of the cameras are regular visible light cameras that are used to detect vehicles during the day, while the other two are infrared cameras that can help detect vehicles at night as well as during bad weather.

In addition to the cameras, two radar sensors (R17 and R18) are used to add sensor coverage to the area just outside the median to detect vehicles making left turns onto the mainline.


Figure 58. Sensor coverage along crossroads at the Hwy52 intersection.

The video signal from each camera is sent to a video amplifier at the base of the camera pole, which sends two amplified signals back to the main controller. The second signal is meant for redundancy in case of cable failure with the first input. At the main controller, the signal is split with one input going to the image-processing computer and the other to the data acquisition computer (See Figure 59). At the image-processing computer, a four channel input image capture card is used that can receive video signals from up to four cameras. The board provides images from the cameras to the image-processing module at about 10 Hz for each of the four channels.

Figure 60 shows a picture of the infrared camera, the visible light camera and an infrared illuminator mounted on top of a camera mast. The infrared illuminator was used to enhance the efficacy of using an SDRC to perform tracking in low-light conditions.


Figure 59. Video Signal Dataflow.


Figure 60. Infrared camera, visible light camera and the infrared illuminator mounted on the camera mast.

### 5.5.2 Image Processing Techniques

### 5.5.2.1 Visible-light Camera Image Processing

Separate preprocessing steps are used for to process the image from the visible light cameras as well as the infrared cameras. All the image processing for the visible light cameras are done using grayscale images. The steps in processing the images from a visible-light camera are shown in Figure 63. Before any of the processing is done a region of interest is defined, which states the boundaries to use for the image processing (See the red polygons in Figure 61).


Figure 61. Regions of interest defined at module startup.

To detect a vehicle in an image from the visible light camera, it is critical to have a good reference background image. The background image must also be capable of adapting to the current lighting conditions. When the program initializes, an initial background image is obtained, and this image adapts to the current lighting conditions by a method of weighted averaging of the subsequent images from the camera. With an initial image obtained, the background image for the next step of processing can be given by the equation:

$$
B_{i+1}(x, y)=(1-\alpha) B_{i}(x, y)+\alpha C_{i}(x, y)
$$

where,
$B_{i}$ is the current background image
$C_{i}$ is the current image from the camera
$\alpha$ is the averaging weight that is determined from the current image

The background-generation module continues to add to the background a weighted average of the current image, by giving a higher weight to motion-free images and a very low weight to an image that contains a vehicle. Hence the averaging weight factor $\alpha$ is determined from the current image based on whether an object is present in the current image. The background averaging adapts to the changes in the environment over time, and allows the image processing module to robustly detect vehicles under most lighting conditions.

Each subsequent image captured from the camera is subtracted from the background image to separate relatively different pixels in the new image from the background. Once a subtracted image is formed, the result is passed through a threshold function. The threshold function produces a binary image in which pixels are segmented into black and white; the black pixels correspond to background and white pixels correspond to foreground. In a single pass, each pixel in the image is compared with a threshold to determine its state in the binary image. If the pixel's intensity is higher than the threshold, the pixel is set to white in the output and if it is less than the threshold, it is set to black. The threshold function truly highlights regions created by the presence of a vehicle in the new image, as well as reduces the noise in the image. An example of the threshold function is shown in Figure 62.


Figure 62. Thresholding Example

A blob analysis of the thresholded image is then performed to determine if a vehicle exists in the image and its position in the image. To determine the presence of blobs, the image is processed to group nearby pixels together as one. If a blob meets a specific size threshold, it is assumed to be a vehicle and the blob position and its rectangular size are obtained in pixel coordinates. The blob position in pixel coordinates is then transformed into state-plane coordinates before it is sent to the sensor-collector module in the main controller.


Figure 63. Processing of images from a visible-light camera.

Observation and testing so far has shown that the background averaging method described above helps to reliably separate vehicles from the image in most weather conditions. False detections, however, occur when it is dark and headlights from vehicles produce ghost targets in the image. The problem caused by headlights from vehicles is illustrated in Figure 64. To avoid this problem, the processing of the visible light cameras is automatically turned off at sunset and it is turned back on at sunrise.


Figure 64. Effect of vehicle headlights during low-light conditions.

### 5.5.2.2 Infrared Camera Image Processing

For the infrared cameras, a different approach is used to acquire the thresholded image for blob analysis. The infrared cameras work by measuring the temperature of the area in its field of view. The camera can be set with an isotherm temperature level; all pixels that lie above this temperature level are automatically highlighted in red. This feature was exploited to simplify the image processing of the infrared images. The isotherm level is set to a temperature that is above the road temperature, but below the temperature of vehicles.

To ensure that the isotherm temperature level is set correctly and adapts to the environmental conditions, another process monitors the ambient temperature levels. This process reads the average temperature level of the image output from the infrared cameras and sets the isotherm temperature level based on this temperature. A running average of the temperature level is maintained and this allows the isotherm level to slowly adapt to the changing conditions. The speed of adaptation affects how well a vehicle can be segmented from the image. If the adaptation is too slow, the temperature changes between morning and noon will cause the road surface to appear above the isotherm level, thus leading to false targets. If the adaptation is too
fast, then a vehicle that waits for a few minutes in the view of the camera will eventually not stand out, as the isotherm level will adjust to be as high as the vehicle temperature.

Before any of the processing is done a region of interest is defined which states the boundary of image processing. The first image in Figure 65 shows the output of the infrared camera with an object that has a temperature above the isotherm level. The section below the vehicle is hotter than the isotherm level and hence stands out in red.

After the image is read from the camera, it goes through a threshold function that segments all the red pixels into a white pixel, leaving all the other pixels black. The second image in Figure 65 shows the binary thresholded image that has all the red in the original image set to 1 in the binary image.

The final step in the processing is a blob analysis and this is done in a similar to that described for the visible light cameras. After the blob analysis is done, the position of the target in pixel coordinates can be obtained.

### 5.5.3 Calibration Procedure

In order to convert the target position from image pixel coordinates to state-plane coordinates, each camera needs to be calibrated to determine the parameters for this conversion. The coordinate conversion requires the knowledge of the region of interest (ROI) in the image and the corresponding opposite corners of the ROI in state-plane coordinates.

The state-plane coordinates of two opposite corners of the ROI are measured using a DGPS system, and this is used as a starting point for the calibration. A probe vehicle is driven on the lanes that are in view of the sensor in the ROI, while its state-plane coordinates are visualized with respect to the map. To adjust the state-plane coordinates, the initial corner coordinates obtained from the DGPS unit are adjusted slightly until the target is accurately placed on the map.


Image acquired from the infrared camera. The heat signature below the vehicle is higher than the isotherm and is set to the color red by the camera


Thresholded image where the red pixels in the region of interest are set to 1 in the binary image


Region of Interest

Final tracked object with a squre drawn around the blob

Figure 65. Processing steps for images from the infrared camera.

Visible light cameras offer significant performance benefits during daylight hours. However, as expected, the ability of a visible light camera to produce images of sufficient contrast during low light conditions was insufficient to facilitate accurate vehicle trajectory tracking. Visible light cameras are used to track vehicle trajectories during daylight; IR cameras are used during the evening hours. Switching between daylight and evening is based on sunrise/sunset information that can be determined for a given latitude and longitude by using a standard set of equations. This information provides a consistent means to ensure video tracking quality on a day-to-day basis.

It can easily been seen in Figure 66 the performance advantage offered by the infrared cameras at night. The vehicle in the picture is almost completely invisible to the visible light cameras, while it can clearly be seen with the infrared camera. A test with the infrared illuminator and the SDRC camera showed that even this setup had insufficient illumination for robust target detection.


Figure 66. Night performance comparison of the cameras.

### 5.5.4 Experimental Validation

A similar experiment to the one conducted on the minor road was performed on the crossroads to determine the system performance for this section. Two probe vehicles fitted with high-accuracy DGPS systems were driven along the minor road and straight through to the median. To determine the accuracy of the crossroads system, the time that the probe vehicles left the crossroad was compared to the time the system state of the detected vehicle left the crossroad. This accuracy is critical as the actual time a vehicle leaves the crossroad is use to determine the gap that was accepted by the vehicle. Figure 67 illustrates the dataflow for the experiment.


Figure 67. Crossroads Performance Experiment Dataflow.

The results of one of the experimental runs using a sedan as a probe vehicle is shown in Figure 68. The plot illustrates the errors for when the sedan leaves the median section. The average longitudinal time error for all the experimental runs for the straight through maneuver was found to be 302 ms . This error is minimal and does not significantly affect the measurement of the gaps selected by vehicles making this maneuver.

Sedan on CSAH 9W




Figure 68. Results from an experimental run with a sedan in the median.

## Chapter 6: <br> Communication Systems

During the initial system design effort associated with the rural IDS program, wireless communication was to be used as the primary means of electronic communication. The motivation behind this design premise was that the expense of trenching, installing conduit, and pulling communication cables would far outweigh the cost of configuring a wireless Ethernet network designed to cover1220m x200m area. However, cost estimated returned by the electrical contractor showed the incremental cost of hardwired communication to be relatively inexpensive. Total length of one-inch PVC conduit for the Cat V Ethernet cable for the entire intersection was $\$ 1.08$ per foot; 8,500 feet were used for a total of $\$ 9180$. This represented approximately $9 \%$ of the electrical contractor cost.

Because power is distributed to each of the sensors with a buried line, the only cost associated with buried communication cable is the cost of the cable and the conduit in which it is placed.

### 6.1 Communication System Functional Requirements

The purpose of the communication system is to relay timely sensor information to the main processor in a reliable, consistent, and prompt manner. The following enumerates the communication system functional requirements, which will enable the system to perform as needed.

### 6.1.1 Bandwidth

The communication system must exhibit sufficient bandwidth to pass all data robustly with no packet information loss in normal operating conditions. Communication equipment shall neither cause nor be susceptible to electro-magnetic or radio frequency interference.

### 6.1.2 Commercial off-the-shelf

All communication hardware shall be commercially available, off the shelf equipment.

### 6.1.3 Operating environment

All communication equipment used shall be designed to operate over harsh temperature extremes typical of Minnesota (-40F to 165F).

### 6.2 Description of Communication Systems

### 6.2.1 Hardwired Communication System

### 6.2.1.1 Digital Communication

The Minnesota Rural IDS system uses two proven, conventional hardwired communication technologies; 100Mbit/s Ethernet, and DSL. Each is described below.

### 6.2.1.1.1 $100 \mathrm{Mbit} / \mathrm{s}$ backbone

The main communication backbone is a closed, $100 \mathrm{Mbit} / \mathrm{s}$ Ethernet network. It is constructed from inexpensive, universally available hardware, and offers more than sufficient bandwidth for this application.

### 6.2.1.1.2 Range requirements

The rural IDS system varies a bit from the conventional Ethernet network in that remote sensors are located as far as 731 m ( 2400 ft ) from the main controller cabinet. Because of the safety critical nature of this application, a reliable means to push data 731 m (2400ft) is needed. Conventional Ethernet is limited to a 76 m (250ft) communication run; clearly, this is insufficient for this IDS application.

A number of technologies and approaches to extend Ethernet communications beyond 76 m (250ft) were reviewed. These technologies included Ethernet amplifiers and DSL modems; approaches included the use of multiple Ethernet hubs to extend the effective range of Ethernet communications.

Ethernet amplifiers and the use of multiple hubs were discounted primarily for reliability reasons. Insertion of line amplifiers and hubs adds a significant amount of hardware, and requires multiple cable terminations and connections. Furthermore, failure in one component causes the communication "downstream" to fail because messages are hopped from the furthest station to the central cabinet. The use of multiple hubs and line amplifiers runs contrary to system goals of simplicity and maintainability.

For this application, the most attractive alternative was the use of a DSL modem. DSL offers a maximum range of 1524 m (5000ft), more than sufficient for this application. Moreover, DSL modems offer a wide variety of bandwidths, ranging from 4Mbit/s to $16.7 \mathrm{Mbit} / \mathrm{s}$. These modems are rugged, proven, and relatively inexpensive ( $\$ 240$ for a $16.67 \mathrm{Mbit} / \mathrm{s}$ modem, which is expensive compared to $100 \mathrm{Mbit} / \mathrm{s}$ hardware, but competitive when compared to the complexity of multiple hubs needed to push the signal 2400 feet). Moreover, DSL modems allow up to 1610 m (5280ft) of unbroken cabling, adding to system reliability. The long range of DSL modems allows the communication architecture to be point to point between each station and the central cabinet. An equipment failure using this scheme only affects communication for the one failed station while the others would not be affected. A single pair of modems is needed for each
communication channel, allowing a direct (single cable) connection from the remote sensor to the central processor.

### 6.2.1.1.3 Time synchronization

Time synchronization of all remote processors is performed by using Network Time Protocol (NTP, see www.ntp.org for more information). A Trimble NTP server is located at the main controller cabinet, and uses GPS as the time reference for this system. NTP facilitates the synchronization of the remote computers to the millisecond.

### 6.2.1.1.4 Mainline radar sensor data flow

The path of mainline radar information collected at the intersection is shown in Figure 69 below. Both hardwired and wireless modes of communication are illustrated. With respect to the hardwired system, it is important to note that each sensor station is connected to the central control cabinet by a continuous Cat V cable.

### 6.2.1.1.5 Vehicle classification lidar and radar sensor data flow

The path of information collected at the intersection is shown in Figure 70 below. Both hardwired and wireless modes of communication are illustrated. With respect to the hardwired system, it is important to note that each sensor station is connected to the central control cabinet by a continuous Cat V cable. The wireless system is installed in parallel but isolated from the wired system. This is achieved by using two Ethernet cards in each sensor station computer as well as a programmable switch in the main controller. This architecture facilitates the direct, conflict free comparison of wired vs. wired communication.

### 6.2.1.2 Analog Video Communication

The Minnesota test intersection has four Millerbernd 7HH8650-350-1TS folding camera masts located at the test intersection; two of the masts serve the cross roads (for recording driver behavior in the median) and two serve the mainline (for analyzing and validating the performance of mainline roadside sensors). Analog visible light and thermal imaging cameras both produce NTSC analog signals; however, the video amplifiers provided with these cameras can only drive the signal a maximum of 15 meters. The camera located closest to the main control cabinet requires a cable run of 60 meters; the camera furthest from the control cabinet has a cable run of approximately 400 meters. To reliably push the analog signal these distances, a video amplifier (Marshall VVL 2212) was used to "drive" the video signals to the image capture boards in the main control cabinet. These amplifiers can drive a video signal 460 meters with RG 6 coaxial cable.

At the test intersection, no video multiplexing is performed. Therefore, each camera requires its own amplifier and cable run back to the main control cabinet. Because the RG 6 cable is relatively inexpensive and the incremental cost to increase the diameter of conduit is low, multiple runs of RG-6 were run from the Millerbernd camera masts to the main controller cabinet. This insures that a cable failure can be addressed by replacing the damaged cable, thereby minimizing possible data collection downtime.

The dataflow diagram for the analog communication system is shown in Figure 71 below.


Figure 69. Data flow for Radar sensor data using both hardwired and wireless channels. Dual Ethernet cards are used in each radar computer to isolate the wired from wireless systems. This allows performance of the wireless system to be measured using the hardwired $100 \mathrm{Mbit} / \mathrm{s}$ backbone as a reference.


Figure 70. Data flow for Lidar sensor data using both hardwired and wireless 802.11a. Dual Ethernet cards are used in each radar computer to isolate the wired from wireless systems. This allows performance of the wireless system to be measured using the hardwired $100 \mathrm{Mbit} / \mathrm{s}$ backbone as a reference.


Figure 71. Analog Data Flow for vision-based, hardwired crossroads surveillance system. RG 6 is used for all cabling. The vision tracker computer determines position, speed, and heading for the vehicles found within the camera region of interest; the output of the tracker is sent to the state estimator which fuses data from other remote sensors to determine the state of the intersection.

### 6.2.2 Wireless Communication System

### 6.2.2.1 Digital Communication

The wireless system architecture is based on commercially available, 802.11b hardware. The 802.11 b system operates at 2.4 GHz , and offers a maximum throughput of $11 \mathrm{Mbit} / \mathrm{sec}$. Time synchronization is performed with the wireless system using NTP; NTP is effective if sufficient network data bandwidth exists.

It is important to note that project time constraints prevented the full implementation and testing of the wireless IDS communication system. However, the equipment has been procured and has been installed at the test intersection. In the spring, the wireless communication system will be brought on-line and tested for reliability, robustness, environmental sensitivity, and data transfer rates.

### 6.2.2.1.1 Range

As was the case for hardwired communication, the wireless system is also required to provide signals at a range of up to 731 m . This requirement forced, in part, the selection of 802.11 b hardware over 802.11a hardware; lower carrier frequencies, in general, result in higher RF signal propagation ranges. Range is a greater priority than bandwidth in this application; bandwidth issues are described below.

### 6.2.2.1.2 Bandwidth

As described in section 0 above, maximum communication system range represents a greater system priority than does bandwidth. This is primarily due to the fact that the only available mechanisms to increase communication range are antenna design and placement. Because the radar stations are quite short, options are limited.

With sufficient maximum range assured, bandwidth is address next. Although 802.11b provides a theoretical maximum data transfer rate of $11 \mathrm{Mbit} / \mathrm{s}$, its actual capacity is site specific, and depends on a number of factors including local electromagnetic conditions and sight lines. However, a number of inexpensive solutions exist in the event that available bandwidth becomes an issue.

If bandwidth with a single access point is insufficient, the communication system can be configured with multiple access points to properly balance network loading. Figure 69 and Figure 70 show multiple access points at the central control cabinet. For instance, each of the multiple access points can be assigned a unique SSID; once SSIDs are established, station adapters at each remote station will be assigned to one of the multiple access points. Because access points are inexpensive, this approach is cost effective, and will result in reliable data transmission.

### 6.2.2.1.3 Mainline radar sensor data flow

The path of mainline radar information collected at the intersection is shown in Figure 69 above. If multiple access points are required, potential signal distribution schemes include distribution by intersection leg, intersection quadrant, or sensor type.

### 6.2.2.1.4 Vehicle classification lidar and radar sensor data flow

The path of information collected at the intersection is shown in Figure 70. If multiple access points are required, signal distribution will be consistent with the distribution of mainline radar data as described above.

### 6.2.2.2 Analog Video Communication

The hardware and range information associated with the transmission of video data from the camera masts to the main controller cabinet were addressed in section 0 . The data flow diagram for wireless transmission of video data captured at the test intersection is shown in Figure 72 It should be noted that although the wireless system was designed, it was not implemented at the test intersection.


Figure 72. Wireless Data Flow for Wireless, vision-based crossroads surveillance system.
A number of commercial off-the-shelf wireless video Xmitter/Receiver systems are available, and would be relevant for this application. The tracker block determines position, speed, and heading for the vehicles found within its region of interest; the output of the tracker is sent to the state estimator, which fuses data from other remote sensors to determine the state of the intersection.

## Chapter 7: <br> Computation System Hardware

### 7.1 Radar Station Computation Hardware

Since the computers at the radar station only require doing a small amount of processing, the computational system at these stations was minimal. An Octagon 2050 PC/104 platform based CPU card was used with a 64 MB compact flash card as the storage device.

## Specifications:

CPU: Low-power, $5 x 86$ CPU, 128 MHz
RAM: 32 MB SDRAM SMT
Ethernet: 10/100 BASE-T, Intel 82559ER
Serial: $\quad 2$ serial ports, 16C550 compatible, RS-232/422/485
Parallel: LPT1, bi-directional
EIDE: Supports two, HDD, CD-ROM, etc.
Floppy: Supports one drive, all sizes
Keyboard: Standard AT keyboard input
Mouse: Standard AT mouse input
Expansion: 16-bit PC/104 expansion
Watchdog: Programmable 0.5-64 seconds
Power: $\quad 5 \mathrm{~V}$ only, 900 mA maximum
Temp. range: $\quad-\mathbf{4 0}$ 和 $\mathbf{8 5}{ }^{\circ} \mathrm{C}$, operating; $-50^{\circ}$ to $90^{\circ} \mathrm{C}$, non-operating
Shock:
Vibration: $\quad 5 g$. random, $10-500 \mathrm{~Hz}$
Size: $3.550 "$ x $3.775^{\prime \prime}$
Storage device: $\quad$ 64MB Compact Flash card
OS:
QNX v6.2

### 7.2 Lidar Station Computation Hardware

Processing of lidar information is significantly more complicated than processing radar data. Lidar data arrives at 35 Hz compared to 10 Hz from the radar. Moreover, some lidar stations are also required to process radar data as well. For these reasons, the computers at the lidar station are more powerful than the one used at the radar stations. For the processing computer, an Octagon PC770 EBX platform board was chosen. The lidar sensors also require a special RS485 PCI card that can communicate with the sensor at 500 kBaud , and hence a PC/104 to PCI interface board is also required. A 256 MB compact flash card was used as the storage device for these computers.

## Specifications:

CPU:

| RAM: | 128 MB SDRAM |
| :--- | :--- |
| Ethernet: | Dual 10/100 BASE-T, Intel 82559ER |
| Serial: | 4 serial ports, 16C550 compatible, RS-232/422/485 |
| Parallel: | LPT1, bi-directional |
| EIDE: | Supports four, HDD, CD-ROM, etc. |
| Floppy: | Supports two drive, all sizes |
| Keyboard: | Standard AT keyboard input |
| Mouse: | Standard AT mouse input |
| Expansion: | 16-bit PC/104 and 32-bit PC/104 Plus expansion |
| Watchdog: | Programmable 0.5-64 seconds |
| Power: | 5V only, 3A maximum |
| Temp. range: | $-\mathbf{4 0 ^ { \circ }}$ to 85º C, operating |
| Size: | $5.75^{\prime \prime} \times 8.00$ " x 0.8" |
|  |  |
| Storage device: | $256 M B$ Compact Flash card |
| OS: | QNX v6.3 |

Additional Cards:

Quatech DSC300, 2 port RS-485 card (custom for SICK Lidar Sensor)

### 7.3 Main Controller Cabinet Computation Hardware

The main controller cabinet contains four rackmount computers that performing the processing for the system state estimation, video and image processing, data acquisition and an additional computer that acts as the web server, data server and timeserver.

## Main Controller Computer Specifications

CyberResearch CPCV COP-1400 (with an LBJ6 rackmount chassis)

| CPU: | Intel Pentium III, 1.4Ghz |
| :--- | :--- |
| RAM: | 256 MB SDRAM |
| Ethernet: | 10/100 BASE-T, Intel 82559 |
| Serial: | 2 serial ports, RS-232 |
| Parallel: | LPT1, bi-directional |
| EIDE: | Supports four, HDD, CD-ROM, etc. |
| Floppy: | Supports two drive, all sizes |
| Keyboard: | Standard AT keyboard input |
| Mouse: | Standard AT mouse input |
| Watchdog: | Programmable 1-255 seconds |
| Temp. range: | $0^{\circ}$ to 55 ${ }^{\circ}$ C, operating |
| Storage device: |  |
| OS: | QNMB Compact Flash card |
|  | QNX v6.3 |

The other three computers have the exact same computer configuration and the specifications are listed below:

Armorlink SAGP-865EVG (with a Rack200B rackmount chassis)

| CPU: | Intel Pentium IV, 2.4Ghz |
| :--- | :--- |
| RAM: | 1 GB SDRAM |
| Ethernet: | 10/100 BASE-T, Intel 82562 |
| Serial: | 2 serial ports, RS-232 |
| Parallel: | LPT1, bi-directional |
| EIDE: | Supports four, HDD, CD-ROM, etc. |
| Floppy: | Supports two drive, all sizes |
| Keyboard: | Standard AT keyboard input |
| Mouse: | Standard AT mouse input |
| Watchdog: | Programmable 1-255 seconds |
|  |  |
| Storage device: | 80GB Seagate Barracuda ST380011A hard drive |
| OS: | Red Hat Linux v9.0 |

## Additional Cards:

3Com 3C950 Ethernet card for second interface DSPR Research V1304, 4-channel H. 264 encoder and image capture card

200GB Seagate ST320082A hard drives mounted in StorCase DE110 frame for the removable hard drives

## Chapter 8: <br> Data Analysis

The surveillance system thoroughly described in this report provides a rich set of data at high accuracy. The knowledge of the position, speed and heading of every vehicle within the intersection makes it possible to examine driver behavior at rural intersections. Understanding driver behavior at rural intersections is critical to the design of the DII. This section documents the work done for collection, storage and analysis of surveillance system data at the Hwy 52 intersection.

### 8.1 Data Collection and Storage

The surveillance system was designed as a real time system so that it could be deployed as part of an IDS system in the real world. All sensor data is collected and vehicle positions are calculated based on a Kalman filter estimation approach described previously. This allows gap calculations to be performed in a timely fashion so that the information can be relayed to the driver for him/her to act upon. However, further analysis of the data is useful because a post analysis reveals the actual final gap the driver selected, the final maneuver the driver performed as well as the affect on main line traffic. Also, an aggregate analysis can be performed to summarize statistically the general driver behavior at the intersection. This aggregate analysis includes cross correlations with driving maneuver, weather conditions, time of day and vehicle type. Good knowledge of driver behavior at the intersection is important for an IDS system because the DII (gap information) can be tailored for a particular maneuver, geographical region, time of day and vehicle type. The more accurate and pertinent the information displayed to the driver, the more useful and effective the IDS system will be.

### 8.1.1 Method

The method of data collection was influenced by the fact that different sensors operate at different rates and at independent times. There are 26 sensors at the intersection. The radar sends data at 10 Hz , laser sensors at 35 Hz and cameras at 10 Hz . The tracking software collects the sensor data as it arrives and calculates every vehicle's state at 10 Hz using the most recent data (The tracking software internally calculates vehicle states at 20 Hz . It broadcasts the vehicles states at 10 Hz .). This creates a "snapshot" of vehicle states every 100 milliseconds. This snapshot is recorded 24 hours a day. Weather data was concurrently collected from an RWIS weather station one mile north of the intersection adjacent to Hwy 52. Weather data is periodically retrieved from a MN/DOT server. Finally, four channels of video are compressed, and archived on a University of Minnesota server. The video was encoded to compressed video files to reduce storage requirements.

### 8.1.2 Data Flow and Structure

The communication architecture was documented in detail in the previous chapters; a brief overview is presented here. Recall that each sensor station is hard wired to the central cabinet. The central cabinet has four rack mount computers; the central processor, the data server, the image processor and the Intersection Data AcQuisition System (iDAQ). The central processor receives all sensor data and computes vehicle states and gaps. Data is sent from the sensor stations when it becomes available (Figure 73). The sensor collector module that runs on the central processing computer, assembles all the sensor data, and sends it to the vehicle tracker for processing. The raw sensor data and processed vehicle state data is then sent to the data server, also residing in the central cabinet.


Figure 73: Data flow diagram.
This shows sensor data flowing from the sensor stations to the sensor collector module in the central cabinet. The data is then passed to the data server where it is available for any application in the wired and wireless networks.

The data server computer provides a central temporary storage place for all data flowing through the system and routes this data to requesting clients. The data server is the connection point between the wired and wireless networks so data can be served to both wired and wireless devices. Laptops were used to visualize sensor data while at the intersection for demonstration and debugging purposes.

The image processor receives video streams from two visible and two infrared cameras. It extracts images from the streams and processes those images to estimate vehicle states. The image processor sends the computed vehicle positions to the sensor collector module in the central processor.

Four streams of data are produced by the system; raw sensor data, tracked targets data, sensor status information, and gap data. The raw sensor data is a collection of all the sensor data received by the central processor. It is stored so that algorithm development could be implemented off site using real sensor data. The tracked targets data is the output of the tracker, which is the Kalman filter based vehicle state estimator. All the tracked vehicle states are recorded in this data stream. Sensor health and communication status are continually monitored by the system. This is done so faults can be detected and either tolerated or flagged for repair. In addition to being available in real time, this data is stored. Finally, gap time for each vehicle was calculated. The gap was defined as the time required for a vehicle on the main line to reach the middle of the intersection assuming the vehicle maintained its current speed and acceleration. The gap data stream contains the primary, secondary and tertiary vehicle gaps to the intersection for every lane of traffic on mainline. The primary gap is the smallest time gap; the secondary gap is the next smallest and so forth. All data streams are produced every 100 milliseconds (10 Hz ) and represent a snapshot in time of the state of the intersection.

As mentioned in previous chapters, all the computers in the surveillance system synchronize their system clocks so that all data is tagged with a common time reference. A Network Time Protocol (NTP) server connected to a GPS unit is used to synchronize time between computers (see www.ntp.org for more details). The NTP server gets time information from a GPS unit mounted on top of the central cabinet and uses this information to set its clock. Daemons running on all networked computers synchronize their clocks by communicating over the network. This allows the central processor to calculate the time delay in receiving sensor data, which is used in the estimator. It also provides a common time reference used on all data and video streams. This makes the reconstruction of events (collisions and near collisions) possible. The consistent time reference allows the playback of raw sensor and tracked vehicle information on a visualizer for a particular moment in time. It also makes it possible to quickly find video segments for any desired time period.

### 8.1.3 Data Collection and Storage

The surveillance system not only calculates vehicle states in real time, but it can also store all data streams for further analysis. The Intersection Data AcQuisition (iDAQ) system was designed for this purpose.

The iDAQ runs on a rack mount computer using the Linux Operating System. It runs a video capture board with the ability to capture four channels of video (more cards can be added to provide more channels) in real time. It encodes and compresses the video (and audio) in MPEG Layer 4 file format, which is a compressed video/audio format. The iDAQ receives engineering data by communication with the data server and writes all data streams to a 200GB removable hard disk (Figure 74).


Figure 74: Data flow diagram for data collection system.
The iDAQ receives engineering data and video feed from the cameras. It stores the data and video on a removable hard drive.

The engineering data is stored as ASCII text files in a database "friendly" format. This format allows direct insertion into a PostgreSQL database (see www.postgresql.org for more details).

PostgreSQL is mature open source database software. It has the built in functionality to perform queries remotely using the SQL query language. Numerous commercial and open source software packages are available to query a PostgreSQL database.

Both engineering and video data are stored on a removable IDE hard drive. The 200 GB drives can store two weeks of full time video and engineering data. The hard drives are periodically pulled from the iDAQ computer at the intersection and brought back to the University of Minnesota for analysis and archival. Video data, although compressed, consumes much more disk space than engineering data; thus video files are stored for four weeks and then discarded. Videos of particular events of interest can be placed into long term storage if desired. Events can be culled from the engineering data and the time stamps used to find the video file of the event. The video files have the common reference time stamp drawn as an overlay. This allows the playback of the precise moment of an event of interest like a collision or near miss. Video containing interesting events is retained. Engineering data is not discarded, but is permanently stored on a Terabyte server at the university.

### 8.2 Data Processing

The data collected at the intersection are voluminous and thus required a proven method of storage and retrieval. Data is converted and inserted into a master database. Databases are designed to hold large amounts of information and come with powerful tools to quickly retrieve specific pieces of a huge data set. This is an important requirement for the data collected by the surveillance system at the intersection.

### 8.2.1 Creation of Database Tables

The data collected by the surveillance system is rich in information, but is not in an ideal form for analysis. Macroscopic analysis requires further processing the data into a more friendly form so that a flexible data retrieval system can be created.

As previously mentioned, the iDAQ records engineering data as ASCII text files that are structured to be compatible with PostgreSQL databases. Batch programs are run on a newly received hard drive that copy the data from the removable hard drive and insert it into a master database on a terabyte server (Figure 75). Four tables are created from the four data streams recorded by the iDAQ. A fifth table of weather data is created by an automated module that downloads the weather data from a MN/DOT web site.

A second batch module queries for the newly arrived records and creates (or inserts into) two new tables. The first is an intermediary table consisting of vehicles that made a maneuver to/from the minor road (county road 9) to/from the mainline (US highway 52). These Vehicles of Interest (VOI) are then processed further to determine what maneuver was made and what gaps were accepted for each maneuver. A final table is created (or inserted) containing the accepted gaps for each VOI.


Figure 75: Data flow diagram for data processing and analysis.
Batch programs insert text data into a database. A query module extracts desired data into a report.

### 8.2.2 Queries

The seven tables in the database contain all the information necessary to cull desired information out of the database. A GUI program was written that uses the SQL query language to remotely query the database (see www.sql.org for more details). SQL is an industry standard querying language used to query different vendors' databases. The query module was customized to query for gap information cross referenced with several data sets.

### 8.2.2.1 Gap Statistics

Driver selected gaps have variation due to many factors. The driver herself plays the largest role in gap selection, but other factors also play a role. Weather, time of day, traffic conditions, maneuver type, and vehicle classification all have influence in the gaps drivers select. The main goal of the data analysis was to determine what conditions affect the driver selected gap and by how much. This information can be used to tailor a DII advisory based on the situation.

### 8.2.2.1.1 Definition of Gap

A gap can be defined in a number of different ways. A gap can be defined as the time the driver makes the decision to take a gap, the time when the vehicle starts to enter the intersection, when the vehicle is in the middle of the intersection or when the vehicle clears the intersection. All are valid definitions. The first definition is difficult to measure using vehicle states alone. The second definition is difficult to measure because many vehicles "creep" past the stop bar before actually taking the gap. Choosing at which position the driver accepted the gap is difficult. The third definition is measurable and is the gap when the minor road vehicle is in harm's way, in the middle of the intersection. For these reasons it was decided for the following analysis to calculate the accepted gap at the time when the minor road vehicle left the minor road and is thus in the path of traffic on the mainline. The gap time is defined as the time it would take a vehicle on the mainline to reach the exact middle of the intersection if its speed and acceleration were held constant. This provides a consistent gap definition that is measurable and corresponds to when the minor road vehicle is most vulnerable to a collision. The gaps were calculated for each lane on the mainline. The smallest three gaps for each lane were recorded.

In order to locate detected vehicles on the road and to determine the time of gap acceptance, a highly detailed digital map was created. This map included all the lanes of traffic of both the minor and mainlines of the intersection [8]. Each lane was divided into regions as shown in Figure 76. The tracking software calculates the region in which every detected vehicle was located every 100 milliseconds. In order to define the moment in time the gap was accepted, regions were selected for each possible maneuver. The time stamp corresponding to the time when a vehicle left the selected region was flagged and the gap state estimate was retrieved for that time stamp. For straight crossings, regions were selected such that the minor road vehicle completely left the stop bar area and was in the middle of the intersection. For right hand merges the region was selected as the first section where the merging vehicle is located within the right hand lane of the mainline. For left hand merges, the region was chosen as the last region of the median, after which the vehicle is completely within the mainline traffic lanes. The region
selections were consistent with the gap definition in the previous paragraph and provided information about the state of the intersection at the most critical time, when the vehicle was exposed to the fast moving mainline traffic.


Figure 76: Region map of US Highway 52 and Goodhue Country Road 9.

### 8.2.2.1.2 Time of Day Effects

Visibility changes significantly between sunlight and dark conditions. This affects the perception of the distance and speed of oncoming vehicles. During daylight conditions the whole vehicle body can be seen and its size and change in size give estimations of the distance and speed of an approaching vehicle. At night, only the headlights are visible and the driver must estimate the approaching vehicle's distance and speed based on the spacing and intensity of the headlights. Since gap selection is the result of the driver's estimate of vehicle distances and speed, day and night effects were analyzed. Since all data is coded with the time, it was straight forward to query for data during time durations.

### 8.2.2.1.3 Vehicle Maneuver Effects

The minor road vehicle has three options when approaching the mainline; turn left, go straight, or turn right. Each of these maneuvers has a different gap requirement. For a straight through maneuver, the smallest gap is required because the vehicle has to only accelerate and cross the mainline. For a right hand turn, the minor road vehicle has to merge into the main line traffic. It needs enough of a gap to not only enter traffic, but also accelerate up to the local speed of the mainline. This clearly requires more time than crossing the main line traffic.

Maneuvers were categorized by where the tracked vehicle was first detected to where the same vehicle left the surveillance system detection region. This resulted in 10 possible maneuvers for the intersection of US 52 and Goodhue County Road 9. Some maneuvers can be broken down by sub maneuvers. For example, a vehicle coming from county road 9 and crossing highway 52 accepts two gaps and thus has two (straight) sub maneuvers. Table 4 lists all possible maneuvers.

Table 4: Maneuver categories for US 52 and Goodhue County Road 9.

| Maneuver | Maneuver ID | Sub maneuvers |
| :---: | :---: | :---: |
| Cty 9E to Cty 9E | 1 | Straight, straight |
| Cty 9W to Cty 9W | 2 | Straight, straight |
| Cty 9E to US 52N | 3 | Straight, left |
| Cty 9W to US 52S | 4 | Straight, left |
| Cty 9W to US 52N | 5 | Right |
| Cty 9E to US 52S | 6 | Right |
| US 52S to US 52N | 7 | Left |
| US 52N to US 52S | 8 | Left |
| US 52S to Cty 9E | 9 | Left |
| US 52N to Cty 9W | 10 |  |

Queries were written to pull out accepted gaps for each vehicle maneuver. Analysis of the accepted gaps will show if drivers choose different gaps based on the driving maneuver.

### 8.2.2.1.4 Vehicle Classification Effects

Different vehicles have different dynamic capabilities due to mass, length and engine size. Especially important for IDS applications is the acceleration capability of the vehicle on the minor road. Smaller vehicles tend to have higher acceleration capabilities and can take a smaller gap safely. Large vehicles need a bigger gap due not only to their acceleration capabilities but also due to their length. For this reason, a vehicle classification system was installed on county road 9 as part of the surveillance system. The vehicle classification system consists of two laser scanners; one oriented horizontally and one vertically. The horizontally mounted laser scanner provides the length of the vehicle while the vertically mounted laser scanner provides the height of the vehicles. Length and height information was used to classify the vehicles into four bins (Table 5).

Table 5: Vehicle classification groupings.

| Classification <br> Number | Description | Examples |
| :--- | :--- | :--- |
| 1 | Small Passenger Vehicles | Motorcycle, Sedan, Small <br> SUV |
| 2 | Large Passenger Vehicles | SUV, Pickup |
| 3 | Small Commercial Vehicles | Delivery Truck |
| 4 | Large Commercial Vehicles | Semi Truck and Trailer |

Once classified, a query was written to pull out gap data for each vehicle type so that effects in vehicle classification can be examined. If the effect is significant, a vehicle classification system must be considered for an IDS implementation. The accepted gap differences for each vehicle class can be integrated into the algorithm to trigger the DII.

### 8.2.2.1.5 Effect of Waiting Time

Deployment of a rural IDS system raises the question of whether drivers maneuver through split highways in one step or two steps. This could influence the configuration of the DII. If sign based, does an IDS system need two signs, one near the stop sign and one at the median? To answer this, the surveillance system (cross road subsystem) continuously monitored vehicles in the median. This data was analyzed to determine how long a period of time a vehicle spent in the median. This gave insight into how many drivers took two distinct gaps or took the whole maneuver as one gap.

Waiting time can also affect gap selection. Frustration and impatience can cause drivers to select smaller gaps than they normally would. The effects of wait time will be measured at the stop bar and in the median.

### 8.2.2.1.6 Weather Effects

Different weather conditions require different gap selection. This is especially true during snow and ice conditions where vehicle dynamics are greatly affected. Also, visibility conditions can cause a change in driver's gap selection due to the inability to estimate oncoming vehicle distance and speed. For these reasons, weather data was collected and cross referenced with accepted gaps to determine correlations between weather conditions and gaps. If significant, weather conditions can be added to the DII triggering algorithm to provide safe gap information to the driver for a deployed IDS system.

### 8.2.2.1.7 Identification of Near Misses/Collisions

The ultimate goal of a rural IDS system is to reduce or prevent collisions due to poor gap selection. Since collisions at a particular intersection are rare, another measure of system performance is desirable. Near misses can provide insight into poor gap acceptance decision by drivers. Reduction in the number of near misses indicates the system is helping the drivers choose safe gaps. An analysis of small accepted gaps was performed to determine what situations are over represented with respect to small gaps. It was also desirable to pull out near miss conditions so that the video files could be viewed for the exact period of time of the incident. For these reasons, a querying routine was implemented to extract near misses and collisions for analysis.

### 8.2.2.1.8 Specialized Queries

The data recording and analysis software was designed to be flexible. Any recorded data can be cross-referenced with any other recorded data with little effort. The addition of new queries can be easily implemented as the need arises.

### 8.3 Data Analysis

The IDS surveillance system was implemented and data collected 24 hours a day during the winter months of 2005. As described in the previous section, hard drives were taken from the intersection, processed, and stored at the University of Minnesota. This chapter documents the analysis of the data collected at the intersection of US Highway 52 and Goodhue County Road 9.

### 8.3.1 General accepted gap analysis

Data described herein was collected between the dates of February 1 to March 29, 2005. As described in section 0 on page 119, an accepted gap was defined at the time the minor road vehicle was in the intersection. Figure 77 shows a histogram with 0.25 second bins of all the
accepted gaps for all vehicles crossing or entering Highway 52 during this time period. Similar histograms will be used throughout this section to provide a visual representation of the accepted gaps. The maximum gap times are limited by the extent of coverage by the surveillance system (17 seconds) but can be larger when vehicle velocity decreases in a turn lane due to preparation for a maneuver. Most accepted gaps were between 4 and 12 seconds with the maximum count at 7 seconds. A sharp drop off in gaps occurs at around 4 seconds, below which few people took gaps. Similarly, a drop off in the number of gaps accepted occurred at 12 seconds.


Figure 77: All accepted gaps between February 1 and February 22, 2005.
In a gap assistive system small gaps are of particular interest. Reduction of small gaps is critical in the reduction of near misses and collisions. Conversely, at some point the gap becomes so large that the decision to proceed really is not much of a decision. In order to obtain a metric for gap acceptance in true gap selection situations, statistics on gaps of less than 10 seconds were calculated. These "smaller" gap statistics can be compared with the overall gap statistics to determine how much of the gap acceptance numbers are caused by available gaps. The available gap influences the accepted gap because the probability of gap acceptance increases with gap size [12]. A histogram of gaps less than ten seconds with bins of 0.25 seconds is shown in Figure 78. The histogram shows a continual drop off in the number of accepted gaps as the gap time decreases. There is a sharp drop at four seconds, below which the histogram shows a Gaussian like tail.

Table 6 shows the relevant statistics for all the recorded gaps at the test intersection. In this section each histogram figure will be followed by a table with statistics for the data shown in the histogram and the statistics for gaps less than 10 seconds. The mean accepted gap (column 3 ) was 10.2 seconds with a standard deviation (column 4 ) of 4.1 seconds. The median ( $50 \%$ ) gap was 9.7 s . $95 \%$ of the accepted gaps were greater than 4.4 seconds and $99 \%$ of the gaps were greater than 3.1 seconds. That means $1 \%$ of all gaps were accepted with three seconds or less time remaining before a vehicle on the mainline arrived. For vehicles accepting a gap less than 10 seconds, the mean gap was 7.0 s with a 1.9 s standard deviation. The mean was 7.0 seconds.

AASHTO recommends in their 2001 specifications for intersection sight distance that a safe gap be 7.5 sec for passenger cars, 9.5 for single-unit trucks and 11.5 sec for combination trucks [13]. The fact that $1 \%$ of the vehicles chose a gap of 3.1 seconds or less is alarming given the AASHTO recommendation for safe gaps. This is less than half of the safe gap for passenger cars. It is clear that some drivers are accepting gaps at a fraction of what AASHTO considers a safe gap.


Figure 78: All accepted gaps below 10 seconds.

Table 6: Gap statistics for all accepted gaps and gaps of less than 10 seconds.

| Total Measured | $\begin{gathered} \hline \text { Gaps }< \\ \text { 10s } \end{gathered}$ | Mean Gap |  | STD |  | $\begin{aligned} & \text { 50\% } \\ & \text { Gap } \end{aligned}$ |  | $\begin{aligned} & 95 \% \\ & \text { Gap } \end{aligned}$ |  | $\begin{aligned} & \hline \text { 99\% } \\ & \text { Gap } \end{aligned}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Gaps |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| 9108 | 4808 | 10.2 | 7.0 | 4.1 | 1.9 | 9.7 | 7.2 | 4.4 | 3.8 | 3.1 | 2.8 |

### 8.3.2 Intersection Zone Analysis

As explained above, the intersection map was divided into regions from which gap definitions were assigned. The regions were grouped and assigned to a zone. A zone is a group of regions defined to make analysis of driver maneuvers more manageable. The most relevant zones for the analysis of the effect of zone entry to gap selection are shown in Figure 79. Zone 1 contains all the regions on county road 9 to the west of the intersection. Zone 2 similarly contains all the regions to the east. Zone 7 and 8 contain all the regions for vehicles in the median, traveling east and west respectively.


Figure 79: Map of Highway 52 intersection showing region and zone definitions.

The purpose of analyzing the accepted gaps in these zones is to determine whether the area in which a driver selects a gap influences the decision. Figure 80 shows the histograms of the accepted gaps for the four zones shown above. Vehicles that entered from zone 1 and 8 had a significantly lower mean accepted gap as well as a lower standard deviation than vehicles entering in zone 2 or zone 8 (Table 7). For gaps less than 10 seconds, the same trend held. Vehicles leaving zone 1 and 8 have to cross or merge with the southbound lanes of US 52. Vehicles leaving zone 2 and 7 must cross or merge with the northbound lanes of US 52. It appears that gap acceptance was related to which leg of the highway vehicles were crossing/merging.


Figure 80: Accepted gap histograms for the four zones in Figure 79.

Table 7: Gap statistics for the four zones in Figure 79.

| Time Period | Total Gaps | $\begin{gathered} \text { Gaps } \\ <10 \text { s } \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | 95 \% Gap |  | 99\% Gap |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| Zone 1 | 1466 | 980 | 8.6 | 7.1 | 2.8 | 1.8 | 8.6 | 7.3 | 4.3 | 4.0 | 2.9 | 2.8 |
| Zone 2 | 2307 | 616 | 12.9 | 7.7 | 4.1 | 1.7 | 12.9 | 8.1 | 6.3 | 4.1 | 3.9 | 3.1 |
| Zone 7 | 2888 | 1449 | 10.6 | 7.3 | 4.2 | 1.8 | 10.0 | 7.5 | 4.6 | 4.0 | 3.5 | 3.0 |
| Zone 8 | 2106 | 1592 | 7.8 | 6.6 | 2.8 | 1.9 | 7.5 | 6.6 | 3.7 | 3.5 | 2.7 | 2.7 |

In order to better understand why vehicles took such different gaps when crossing/merging the different legs of US 52, an analysis on traffic flow was conducted. Since the surveillance system captures the state of all vehicles in the intersection region of coverage every 100 milliseconds it was possible to count the vehicles on each leg. Samples of the intersection state were selected at one minute intervals and counted for a one week period from February 02 to February 08. The summation showed that 27,299 vehicles were tracked in the northbound lane and 25,573 were tracked in the southbound lane. The northbound lane had a higher traffic rate than the southbound lane. Clearly, average traffic flow rate was not the cause of the mean accepted gap differences measured for the four zones. It would be expected that the leg with the higher average traffic rate would have the smaller gaps.

Samples of the intersection state were again collected for one day (February 2) but taken every ten seconds. This allowed the plotting of the number of vehicles tracked by the surveillance system on US 52 (Figure 81) over a period of time. The figure shows that traffic on the northbound lanes is indeed higher; however, the traffic on the southbound lanes has more variability. At times there are no vehicles within the surveillance system region of detection for the southbound lanes. At other times there were several vehicles. The northbound lanes showed a more uniform traffic flow. There were two or more vehicles detected at most times. For the week, the mean traffic rate for the southbound lanes was 2.9 vehicles per sample while the northbound lane was 3.1. The standard deviation, however, was 3.4 for the southbound lanes and 2.8 for the north.

The difference in traffic patterns can be explained by geography. Eight miles to the north of the intersection is the city of Cannon Falls. There are two signalized intersections on US52 in Cannon Falls. To the south the closest city is Zumbrota, 12 miles away. The highway does not stop in Zumbrota. The signalized intersections in Cannon Falls cause the traffic to arrive at the intersection in waves. A period of high density of cars is followed by a period of low density of cars. The lower gaps accepted on this leg of the highway were due to drivers selecting smaller gaps to get through the periods of tightly spaced traffic. In times of light or no traffic on the northbound lanes, gaps are often larger than the region of coverage and the gaps cannot be measured. On the northbound, the traffic was more consistent providing a wider range of gap selection. The higher standard deviation of selected gap on this leg was simply due to a wider range of available gaps.


Figure 81: Vehicle counts every ten seconds for vehicles on US 52 within surveillance system region of detection.

### 8.3.3 Gaps as a function of time of day

Traffic volume varies based on the time of day which means the available gaps also vary. As has already been seen, the available gaps affect the accepted gaps. Darzentas et al documented that smaller gaps with higher variability were observed at night at semi-urban T-intersections [14]. To explore this further, the accepted gaps were culled from the database based on time of the day. The histograms of the accepted gaps are shown in Figure 82 with the associated statistics in Table 8.


Figure 82: Accepted gaps for morning rush, day time, evening rush and night time.

Table 8: Gaps statistics based on time of day.

| Time Period | Total Gaps | $\begin{gathered} \text { Gaps } \\ <10 \text { s } \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | 95 \% Gap |  | 99\% Gap |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| Morning Rush | 1630 | 750 | 10.9 | 7.2 | 4.2 | 1.8 | 10.4 | 7.4 | 4.6 | 4.0 | 3.7 | 3.0 |
| Day <br> Time | 4583 | 2464 | 10.1 | 7.1 | 4.0 | 1.8 | 9.6 | 7.3 | 4.3 | 3.8 | 3.1 | 2.9 |
| Evening Rush | 2313 | 1360 | 9.7 | 6.9 | 4.1 | 1.9 | 9.1 | 7.0 | 4.2 | 3.7 | 3.1 | 2.6 |
| Night <br> Time | 582 | 234 | 11.3 | 7.2 | 4.3 | 1.8 | 11.0 | 7.5 | 4.6 | 3.9 | 3.4 | 3.0 |

The evening rush hour had the lowest average gap, followed by daytime, the morning rush and nighttime. It was somewhat surprising that the morning rush hour had a larger average accepted gap than the daytime. However, further analysis showed that the mean gaps corresponded with average traffic on the mainline (Figure 83). The tracked targets table was sampled every minute for one week. The average detected vehicles were calculated for every UTC hour (Central Standard Time (CST) is UTC minus 6 hours). The UTC day starts at 6 pm CST, which is when the rush hour starts to wane. The traffic rate decreases until 11 UTC (5 CST) and increases throughout the morning rush hour. However, the traffic rate keeps increasing throughout the day peaking at 23 UTC ( 5 pm CST). The traffic rate diagram has a negative correlation with the accepted gap statistics above. The busiest traffic period (evening rush) showed the smallest accepted mean gap while the least busy traffic period (night) had the largest accepted mean gap. Below ten seconds, however, the mean gap is slightly lower for evening rush but the same for the other times of day. It appeared that even as the average gap accepted decreased with increasing traffic rate due to smaller available gaps, the small gap selection was consistent. Drivers were not significantly increasing their risk because the traffic volume changed. Also, there does not appear to be a significant effect based on sunlight. The under ten second mean gap and standard deviation were similar in the night and day hours.


Figure 83: Average number of detected vehicles during a 24 hour period.

### 8.3.4 Gaps for different vehicle maneuvers

Crossing the stream of traffic requires a smaller gap than merging with traffic. This is due to the fact that the minor road vehicle only has to cross the width of the major lanes. When merging, the minor road vehicle has to enter the traffic stream and accelerate to the speed of the mainline. In order to investigate the effect of vehicle maneuver on gap selection, the gaps were crosscorrelated with vehicle maneuver.

Figure 84 shows the histogram of accepted gaps for all straight through, right and left turn maneuvers. It was immediately apparent that there were few left-handed turns. The average accepted gap was lowest for straight maneuver followed by right and then left turns. This agrees well with the literature $[15,16,17]$. This result is important in the design of a DII. Vehicles turning right or left need larger gaps (sooner warning) than vehicles going straight. This result could warrant the need for more than one DII, positioned for each type of maneuver.


Figure 84: Histogram for straight, right and left turn maneuvers.

Table 9: Gap statistics for each vehicle maneuver.

| Maneuver | Total Gaps | $\begin{gathered} \text { Gaps }<~ \\ 10 \mathrm{~s} \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | $\begin{gathered} 95 \% \\ \text { Gap } \end{gathered}$ |  | $\begin{aligned} & \text { 99\% } \\ & \text { Gap } \end{aligned}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| Straight | 6104 | 3724 | 9.4 | 6.9 | 3.9 | 1.9 | 8.8 | 7.1 | 4.1 | 3.7 | 3.0 | 2.8 |
| Right | 2945 | 1064 | 11.8 | 7.5 | 4.1 | 1.8 | 11.5 | 7.8 | 5.3 | 4.2 | 3.6 | 2.9 |
| Left | 59 | 20 | 12.7 | 6.8 | 5.0 | 1.7 | 13.1 | 6.8 | 4.4 | 4.2 | 4.2 | 4.2 |

### 8.3.5 Gaps as a function of vehicle classification

Larger vehicles need larger gaps in order to cross or merge into an intersection than do smaller vehicles due to their larger mass and length. A vehicle classification system was installed on both legs of country road 9 to determine the type of vehicle entering the intersection. The vehicles were classified into four bin; small passenger, large passenger, small commercial, large commercial. The four classification classes were then analyzed for their influence on accepted gap time.

Figure 85 and Table 10 show the accepted gap histograms and statistics respectfully. The numbers for all four-vehicle classes are quite similar. There appears to be no statistical difference in the accepted gap time for a larger vehicle like a semi truck or a smaller vehicle like a sedan. This is somewhat unexpected, as it would be expected that larger vehicles need and would take larger gaps.


Figure 85: Histogram of gaps for each vehicle classification.
Table 10: Gap statistics for each vehicle classification.

| Classification | Total Gaps | $\begin{gathered} \text { Gaps }<~ \\ 10 \text { s } \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | 95 \% Gap |  | 99\% Gap |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| Small <br> Passenger | 2537 | 1384 | 10.1 | 7.1 | 4.0 | 1.9 | 9.5 | 7.3 | 4.3 | 3.8 | 3.0 | 2.9 |
| Large Passenger | 4479 | 2298 | 10.3 | 7.0 | 4.2 | 1.9 | 9.8 | 7.2 | 4.3 | 3.8 | 3.3 | 2.9 |
| Small Commercial | 757 | 403 | 10.1 | 7.0 | 4.1 | 1.9 | 9.6 | 7.2 | 4.4 | 3.6 | 2.7 | 2.6 |
| Large Commercial | 1280 | 697 | 10.1 | 7.1 | 4.0 | 1.8 | 9.6 | 7.3 | 4.4 | 3.9 | 3.3 | 2.9 |

The definition of gap selected for this analysis may have influenced the result. Recall, the definition of gap is at the time when the minor road vehicle completely leaves the minor road and is within the mainline. This definition does not take into account the time to accelerate and move totally into the intersection. It also does not take into account the length of the vehicle. Figure 86 shows lines of constant acceleration on a distance verses time plot. The two horizontal lines represent approximate lengths of a semi truck with trailer and a sedan. For example, at 5
$\mathrm{m} / \mathrm{s}^{2}$ the semi truck would take two seconds to travel its length and the sedan would take one second. At $2 \mathrm{~m} / \mathrm{s}^{2}$ the semi would take over 3 seconds and the sedan would take 1.5 seconds. Now if the sedan accelerates at a higher rate than the truck, which is likely, the difference in time to travel the vehicle length increases even more. That means that drivers of larger vehicles must have decided to take the gap before drivers of smaller vehicles, but ended up accepting the same gaps, based on the definition provided here. In a way, the drivers compensated for their larger vehicles in their decision-making but accepted the same risk by being exposed to the main line traffic with the same gap time margin.


Figure 86: Distance traveled for difference acceleration rates.

### 8.3.6 Waiting for a Gap

Prior work on the effect of the time a vehicle waits for a gap on the accepted gap time has shown a negative correlation $[12,18]$. The longer a driver waits for a gap the smaller the accepted gap. To test whether this is true of the test intersection, an analysis was conducted in which gap times were correlated with time waiting to accept the gap. The analysis was conducted for the vehicles waiting at the stop bar (zone 1 and 2 ) and for vehicles waiting at the yield sign in the median (zone 7 and 8).

The histogram of the times drivers waited at the stop sign zones (1 and 2) of County Road 9 are shown in Figure 87. It should be noted that the time in a zone includes the whole time the vehicle spent in the zone. This includes the time approaching the stop sign until the vehicle left the zone and was in the mainline of traffic either crossing or merging. The time approaching the stop sign should be similar on average for each driver and would simply shift Figure 87 to the left. Based on this figure, times were chosen to reflect the important sections of the histogram. The period of 5 to 12 seconds represents the waiting times prior to the peak, 12 to 17 seconds the
peak, 17 to 25 seconds the majority after the peak and $25-60$ seconds for the people waiting the longest for a gap.


Figure 87: Time vehicles waited for an acceptable gap at the stop signs (zone 1 and 2).

The histograms for the accepted gaps for each time period is shown in Figure 88 with the corresponding accepted gap statistics shown in Table 11. The data shows that the mean accepted gap was the highest for vehicles waiting the shortest amount of time ( $5-12 \mathrm{sec}$ ), but the difference between the last three time periods was small. This is likely due to the fact that the driver waited longer because the gaps were smaller due to heavier traffic. Drivers may accept a smaller gap the longer they wait after realizing that there simply may not be bigger gaps for a while. Also, longer wait times could result in greater frustration and impatience, which leads to smaller gaps being accepted [18].

For accepted gaps less than ten seconds the mean and median gap time are the lowest for longer wait times ( $17-25 \mathrm{sec}$ ). It appears that drivers did slightly alter their risk acceptance while waiting for a gap. Drivers that waited $17-25$ seconds chose gaps an average of 0.3 seconds smaller than drivers that waited only briefly. This is a small effect.

An implementation of a DII could take into account wait time at the minor road. If minor road surveillance sensors are installed, the algorithm for triggering the DII could adjust for the time a vehicle waits at the stop bar. Alternatively, the main line traffic could be continuously analyzed for available gaps and the DII warning algorithm could be adjusted based on available gaps.


Figure 88: Gaps by time waiting at the stop bars (zone 1 and 2).

Table 11: Accepted gap statistics cross referenced with time waiting at the stop bar zone.

| TimeWaitingfor Gap (s) | Total Gaps | $\begin{gathered} \text { Gaps } \\ <10 \text { s } \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | $\begin{gathered} 95 \% \\ \text { Gap } \end{gathered}$ |  | 99\% Gap |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| 5-12 | 219 | 127 | 9.9 | 7.0 | 4.2 | 1.8 | 8.8 | 7.4 | 4.0 | 3.7 | 1.7 | 1.7 |
| 12-17 | 388 | 245 | 9.3 | 7.1 | 3.6 | 1.8 | 8.8 | 7.3 | 4.2 | 3.9 | 3.2 | 3.1 |
| 17-25 | 274 | 157 | 9.5 | 6.7 | 3.9 | 1.9 | 9.1 | 6.9 | 4.2 | 3.7 | 2.8 | 2.8 |
| 25-60 | 213 | 138 | 9.2 | 7.0 | 3.6 | 1.9 | 8.8 | 7.2 | 4.3 | 4.0 | 1.9 | 1.9 |

The effect of wait time on gap acceptance for vehicles in the median was studied by looking at the accepted gaps for vehicles that were in zone 7 and 8 (see Figure 79 for diagram of the zones). A histogram of the time vehicles spent in the median is shown below (Figure 89). It is apparent that most vehicles were in the intersection less than five seconds. In fact, half the vehicles were in the median zone less than 3.6 seconds. Time periods of 0 to $3 \mathrm{~s}, 3$ to $5 \mathrm{~s}, 5$ to 10 s , and 10 to 60 s were selected which corresponds to times before and after the peak. The accepted gaps for these time periods were queried in order to determine the effect of wait time.


Figure 89: Time vehicles waited in median (zone 7 and 8).

The histogram of accepted gaps along with the table of the corresponding statistics is shown in Figure 90 and Table 12. The mean and median accepted gap actually increased as the time waiting in the median increased, then decreased slightly for the vehicles waiting $10-60 \mathrm{~s}$. It is a bit surprising that drivers selected larger gaps the longer they waited in the median. Perhaps the vehicles that were within the median for less than three seconds did not stop at the yield sign, and kept their speed up so that they more quickly crossed or merged with the mainline traffic. Polus [19] studied accepted gaps at yield and stop sign intersections and concluded that the yield-controlled intersection had a lower accepted gap than the stop controlled intersection. Drivers that took the median in one step "rolled through" the median (like a yield controlled intersection) while those that took the median in two steps stopped in the median (like a stop sign controlled intersection). For vehicles waiting longer than 10 s , perhaps frustration caused them to accept a lower gap resulting in a lower mean gap.

For gaps less than 10s the mean accepted gap similar. This means that drivers did not increase their risk when they went through the median without stopping (one step).


Figure 90: Gap histogram for different time spent in median (zone 7 and 8).

Table 12: Gap statistics for different times vehicles were located in the median.

| Time in Median (s) | Total Gaps | $\begin{gathered} \text { Gaps }<~ \\ 10 \text { s } \end{gathered}$ | Mean Gap |  | STD |  | $\begin{aligned} & \hline 50 \% \\ & \text { Gap } \end{aligned}$ |  | $\begin{gathered} 95 \% \\ \text { Gap } \end{gathered}$ |  | $\begin{aligned} & \hline \text { 99\% } \\ & \text { Gap } \end{aligned}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |
| 0-3 | 202 | 139 | 8.9 | 7.1 | 3.5 | 1.9 | 8.6 | 7.2 | 4.1 | 4.0 | 2.8 | 1.7 |
| 3-5 | 416 | 244 | 9.7 | 7.0 | 3.9 | 1.8 | 9.1 | 7.2 | 4.2 | 3.7 | 3.2 | 3.1 |
| 5-10 | 247 | 142 | 9.7 | 7.1 | 3.7 | 1.8 | 9.1 | 7.3 | 4.3 | 3.9 | 2.7 | 1.9 |
| 10-60 | 240 | 148 | 9.3 | 6.8 | 3.9 | 1.9 | 8.7 | 7.0 | 4.0 | 3.3 | 2.3 | 2.1 |

### 8.3.7 Gaps as a function of weather conditions

Minnesota is well known for adverse weather conditions, particularly in the winter. Other parts of the country have their own weather conditions that affect driving conditions. For intersections, gap selection may be affected by weather conditions like visibility and precipitation. For visibility, the ability to see the gap is critical in the gap selection process. Reduced visibility conditions may alter the gap selection decision due to the reduced ability to see oncoming vehicles. Precipitation may affect gap selection since vehicles at the minor road are stopped and must have enough tire-road friction to accelerate through or into the mainline.

Precipitation like snow may cause drivers to adjust gap selection due to poor road surface conditions.

The Minnesota Department of Transportation (MNDOT) has a network of weather sensors around that state that measure current weather conditions (RWIS). One such weather sensor, which is part of the RWIS system, happens to reside just one mile north of the intersection next to US highway 52. The weather sensor provides information on atmospheric conditions as well as surface and subsurface conditions. The sensor data is provided via a MNDOT run web site and was downloaded daily. The data was inserted into the database for easy retrieval.

Visibility is a logical weather parameter that may affect gaps as the ability to see a gap is critical in deciding whether to take it. The visibility data from the weather sensor located one mile north of the intersection for the period of February 1 to February 22 is shown in Figure 91. The sensor records the atmospheric conditions every 20 minutes so the histogram is a count of the number of samples, each representing 20 minutes. Based on the histogram, visibility ranges were selected to determine their effect on gap acceptance; 1200+m, $900-1200 \mathrm{~m}, 500-900 \mathrm{~m}, 0-500 \mathrm{~m}$.


Figure 91: Histogram of visibility measurement from RWIS station one mile north of intersection.

Based on the period of time in which the visibility was within the chosen range, accepted gaps were pulled from the database tables. Shown in Figure 92 and Table 13 are the accepted gap histogram and statistics. The mean and median accepted gaps increased with decreasing visibility. The variance was similar for all the visibility groupings. For gaps less than ten seconds, the mean and median accepted gap times were similar with a maximum at the low visibility range (less than 500 m ). The increase in gap acceptance time with lower visibility conditions was probably due to drivers being more cautious. The last column in the table shows
that drivers on the main line reduced their speed to account for the poor visibility conditions. Reduction in speed causes the gap time to increase given similar spacing between vehicles. Similarly, the minor road drivers may also take less risk when the visibility decreases due to less confidence in their ability to see the gap.


Figure 92: Accepted gaps for various visibility groupings.

Table 13: Gap statistics for various visibility groupings.

| $\begin{aligned} & \text { Visibility } \\ & \text { (m) } \end{aligned}$ | Total Gaps | $\begin{gathered} \text { Gaps } \\ <10 \\ \text { s } \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | $\begin{aligned} & 95 \% \\ & \text { Gap } \end{aligned}$ |  | 99\% Gap |  | Mean speed (m/s) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | <10s | All | <10s | All | <10s | All | <10s |  |
| 1200+ | 4138 | 2340 | 9.9 | 7.1 | 4.0 | 1.9 | 9.3 | 7.2 | 4.3 | 3.8 | 3.0 | 2.8 | 30.3 |
| 900-1200 | 1729 | 906 | 10.2 | 7.0 | 4.2 | 1.9 | 9.8 | 7.2 | 4.2 | 3.6 | 3.0 | 2.6 | 29.7 |
| 500-900 | 723 | 375 | 10.3 | 6.9 | 4.3 | 1.8 | 9.8 | 7.0 | 4.2 | 3.9 | 3.3 | 3.0 | 29.2 |
| 0-500 | 2164 | 1013 | 10.8 | 7.2 | 4.2 | 1.8 | 10.3 | 7.4 | 4.7 | 4.1 | 3.5 | 2.8 | 29.4 |

Precipitation rate was also analyzed for its effects on gap acceptance. Figure 93 shows the histogram of precipitation rates ( 20 minute samples). It should be noted that the zero bin (no precipitation) was by far the most common condition and extended well above shown figure. It
was cropped so that the other bins could be seen. Based on the precipitation rate histogram, four ranges were selected; $0 \mathrm{~cm} / \mathrm{hr}, 0.01-0.25 \mathrm{~cm} / \mathrm{hr}, 0.25-0.9 \mathrm{~cm} / \mathrm{hr}$ and 0.9 to $1.5 \mathrm{~cm} / \mathrm{hr}$.


Figure 93: Histogram of precipitation rates.

The accepted gap histograms and gap statistics (Figure 94 and Table 14) show that the average and mean gap decreased for light precipitation rates, then increased with higher precipitation rate. The variance increased with increasing precipitation rate. The average speed of the main line vehicles decreased slightly with decreasing visibility, which increases the gap time to the intersection for similar distances to the intersection. For accepted gaps less than ten seconds, the mean accepted gap was similar for first three precipitation ranges. The accepted gap was slightly lower for the higher precipitation rate ( $0.9-1.5 \mathrm{~cm} / \mathrm{hr}$ ). This means in periods of high precipitation, the drivers increased their risk.


Figure 94: Accepted gaps for various precipitation rate groupings.

Table 14: Gap statistics for various precipitation rate groupings.

| Precipitation Rate (cm/hr) | Total Gaps | $\begin{gathered} \text { Gaps } \\ <10 \text { s } \end{gathered}$ | Mean Gap |  | STD |  | 50\% Gap |  | 95 \% Gap |  | 99\% Gap |  | Mean Speed (m/s) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | All | <10s | All | $<10$ s | All | <10s | All | <10s | All |  |  |
| 0 | 8044 | 4247 | 10.2 | 7.1 | 4.1 | 1.9 | 9.7 | 7.3 | 4.4 | 3.8 | 3.1 | 2.8 | 30.3 |
| 0.01-0.25 | 343 | 193 | 10.0 | 7.1 | 4.2 | 1.9 | 9.4 | 7.3 | 4.4 | 4.0 | 2.9 | 2.3 | 29.7 |
| 0.25-0.9 | 193 | 105 | 10.5 | 7.1 | 4.6 | 1.8 | 9.5 | 7.2 | 4.6 | 4.3 | 3.5 | 2.7 | 28.7 |
| 0.9-1.5 | 258 | 130 | 10.6 | 6.6 | 4.9 | 1.8 | 10.0 | 6.7 | 4.1 | 3.9 | 3.3 | 3.0 | 29.5 |

### 8.3.8 Small Accepted Gap Analysis

The goal of an IDS system is to increase the safety of the intersection by helping drivers select safe gaps. Since crash events are rare, surrogate measures of the effectiveness for an IDS system need to be developed. Reducing the amount of small accepted gaps is one possible metric that can be used to evaluate the system's effectiveness. If the system reduces the number of small gaps it shows a positive performance benefit.

The analysis in previous sections showed the accepted gaps for different maneuvers, vehicles classifications and different zones. Table 15 shows the number of gaps accepted below four seconds for each category previously analyzed. It also shows the total number of gaps accepted for each category to show whether a category's small gaps are over or under misrepresented. Overall, $3.3 \%$ of measured gaps were below four seconds.

For maneuver type, the straight through maneuver was by far the most commonly observed maneuver (69\%), followed by right maneuver (29\%) and left (1\%). The straight maneuver, however, had $85.8 \%$ of the gaps below four seconds. The straight maneuver was over represented for gaps less than four seconds.

Looking at the zone category, the total accepted gap counts were more evenly distributed. Zone 7 had the highest number of total gaps, followed by zone 2,8 and 1 respectively. The number of gaps less than four seconds was highest for zone 8 followed by zone 1. These zones were over represented for small gaps while zone 2 and 7 were underrepresented.

For vehicle type, the rate of small gaps was similar to the overall rate for each vehicle class. Classification 1 (sedan, small SUVs) has the most number of gaps (42\%) and the most number of small gaps (43\%).

Table 15: Statistics for small gaps compared with the total gap statistics, broken down by category.

| Category | Total <br> Gaps | Total <br> Category | Percent <br> of <br> Category | Total <br> Gaps <br> < 4 s | Total <br> Category <br> < 4s | Percent <br> < 4s |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Straight Maneuver | 9108 | 6104 | 67.0 | 296 | 254 | 85.8 |
| Right Maneuver | 9108 | 2945 | 32.3 | 296 | 42 | 14.2 |
| Left Maneuver | 9108 | 59 | 0.7 | 296 | 0 | 0.0 |
| Zone 1 | 9108 | 1466 | 16.1 | 296 | 58 | 19.6 |
| Zone 2 | 9108 | 2307 | 25.3 | 296 | 25 | 8.4 |
| Zone 7 | 9108 | 2888 | 31.7 | 296 | 68 | 23.0 |
| Zone 8 | 9108 | 2106 | 23.1 | 296 | 145 | 49.0 |
| Classification 1 | 9108 | 2537 | 27.9 | 296 | 84 | 28.4 |
| Classification 2 | 9108 | 4479 | 49.1 | 296 | 148 | 50 |
| Classification 3 | 9108 | 757 | 8.3 | 296 | 24 | 8.1 |
| Classification 4 | 9108 | 1280 | 14.1 | 296 | 38 | 12.8 |

It is apparent that straight maneuvers had the most number of small gaps. Combining this fact with the zone analysis shows that straight maneuvers across the southbound lanes of US highway 52 (zones 1 and 8 ) had the highest number of small gaps. Crossing these lanes from the median (zone 8) is the most common category of small gaps because it combines both overrepresentations, straight maneuvers (only \%1 turn left) in zone 8. Reduction of the rate of small gaps in these areas would signify improvement in the gap decision behavior of the drivers at this intersection.

An interesting result of this analysis showed that traffic patterns had a significant effect on not only the accepted gap, but the high number (over representation) of gaps less than four seconds. It was shown that the stop lights in Cannon Falls eight miles north of the intersection causes the traffic arriving on the southbound lanes of the intersection to arrive in waves. Periods of tightly spaced vehicles follow periods of no vehicles. This highlights an unintended effect with signalized intersections; they cause variable traffic patterns down stream which cause drivers at the downstream intersection to accept smaller gaps.

## Chapter 9: <br> Conclusions

Overview. This report documented the development of a comprehensive intersection surveillance system designed to measure and record driver behavior at rural, unsignalized intersections. This system was developed to serve two specific purposes. The first purpose was to measure and record driver behavior at these rural, unsignalized intersections. Quantification of driver behavior in the real world setting provides the designer of the driver interface the information necessary to optimize the interface in terms of modality, timing and content.. Second, once driver behavior and traffic patterns are understood, the design of a deployable, cost effective system can be optimized. The performance requirements, as well as complexity and cost, for a rural, Intersection Decision Support (IDS) system are significantly less than that needed to fully capture driver behavior at these rural intersections. The performance capability of the surveillance system described herein far exceeds what is needed to support a rural IDS system. For instance, crossroads surveillance is not needed to deploy a rural IDS system, but it provides crucial information needed to determine how drivers negotiate these rural intersections.

The goal of the rural IDS system is to help drivers with gap selection so that they take safer gaps, thus reducing the rate of collisions at rural intersections. IDS system is composed of four major subsystems; sensing, computation, communication and the Driver Infrastructure Interface (DII). This report documented the design, cost and performance of the rural surveillance system, encompassing the sensing, computation and communication subsystems. Research involving the design and development of the DII is documented in Creaser et al [3].

A prototype surveillance system and testing platform was built at the intersection of US Highway 52 and Goodhue County Road 9, near Wastedo, Minnesota. The intersection was designed to test sensing strategies as well as measure driver behavior with respect to intersection maneuvers. Sensors placed adjacent to the roadside measure the location and speed of all vehicles at the intersection. A Kalman filter-based tracking algorithm estimates the state (i.e., speed, location, lane of travel, time to the crossroads) of all vehicles at 10 Hz . A data acquisition system was developed to record all sensor data as well as the state estimator data.

Surveillance System Description and Performance. The sensing subsystem was divided into three categories based on the geometry of the intersection; the mainline, minor road and crossroads subsystems. The mainline system contains sensors that monitor traffic on the fast moving main leg of the intersection. The minor road system monitors vehicles approaching the intersection from the minor road, slower moving leg of the intersection. Finally, the crossroads system monitors traffic in the median.

The mainline system consists of radar placed along the major leg of the highway. Eaton VORAD EVT-300s were used to sense the speed and position of vehicles on US 52. The sensor data was supplied to the tracking software to produce a "state" representation of the intersection. The state consists of the location, speed, and lane of travel, and time to crossroads for every vehicle on the mainline. To test sensor reliability, an experiment was conducted that used a laser trigger to capture images of vehicle passing by on US 52. The laser trigger location and time
were compared with the tracked vehicles to measure reliability. Discrepancies were analyzed by examining the image for the period of time in question. The mainline system detected the main line vehicles with a reliability of $99.99 \%$. Probe vehicles equipped with high accuracy DGPS were used to measure the accuracy of the mainline surveillance system. The position errors were less than 7 m , speed errors were less than 1.6 kph , and the lane assignment accuracy was $95 \%$. Lane assignment errors primarily arise from measurement ambiguity during lane-change maneuvers.

The minor road system consists of EVT-300 radar and SICK LMS200 laser scanners. The radar sensed vehicles approaching the intersection on county road 9 while the laser scanners detected the vehicles as they approached the stop bar. The lasers also performed vehicle classification by measuring the length and height of vehicles passing by the sensors. The classification system was tested using a procedure similar to the mainline reliability experiments. Laser triggers were used to trigger a camera to capture an image of a passing vehicle. The classification system assigns a vehicle to one of four categories; small passenger (sedans, small SUVs), large passenger (SUV, pickup trucks), small commercial (delivery trucks) and large commercial (semi tractor with trailer). The classification system errors were less than $5 \%$ for one classification category and less than $1 \%$ for two classification categories.

The crossroad (median) surveillance system consists of four cameras placed on masts along side two corners of the intersection. Two visible light and two infrared cameras were used to sense vehicles in the median. As noted previously, it is unlikely that the median subsystem will be required for an IDS system deployment. The crossroads surveillance system was implemented in order to measure the time vehicles spent in the intersection (in order to quantify the frequency of one or two step maneuvers) and to determine when the vehicle left the median in order to calculate the accepted gap. The crossroad system was able to measure the time the vehicle left the median with a mean error of 302 ms (measured with probe vehicle). Data collection and analysis indicate that one-half of the vehicles spent less than 3.6 seconds in the median.

Measured Driver Behavior Summary. In order to quantify driver behavior at the test intersection, an analysis was performed which calculated the mean accepted gap. The driver behavior analysis included accepted gap behavior cross correlated with different parameters including entry point (zone), time of day, maneuver, vehicle classification, time waiting for a gap and weather conditions.

The definition of accepted gap used in this report was chosen to be conservative. It is calculated at the time when the minor road vehicle completely leaves the stop bar or median and is exposed to the main line traffic. At that precise time the time gap is calculated as the time it would take for the closest main line vehicle to reach the middle of the intersection if its speed and acceleration were held constant. Using a time gap normalizes the result with respect to speed. It also provides a measure of what risk the driver accepted because they are at their most vulnerable position when exposed to the mainline traffic.

The overall mean accepted gap for the 9108 measured gaps analyzed herein was 10.2 sec with a standard deviation of 4.1 sec . The surveillance system can detect gaps up to 20 seconds (assuming a 100 MPH maximum mainline vehicle speed) and this average included all measurable gaps. To determine the accepted gap for drivers faced with a smaller selection of
available gaps, statistics were calculated for accepted gaps less than 10 sec. The mean accepted gap for gaps less than 10 sec was 7.0 sec with a standard deviation of 1.9 sec . Five percent of drivers selected a gap equal or less than 4.4 sec and one percent chose a gap of 3.1 seconds or less. For gaps less than 10 seconds, one percent of drivers accepted a gap of 2.8 sec or less.

Vehicles crossing or merging with the southbound lanes of US highway 52 had a significantly smaller mean accepted gap than the vehicles crossing or merging with the northbound lanes. An analysis of traffic flow showed that the average traffic volume for both directions was similar but the traffic pattern was different. The traffic on the southbound lanes was more variable. Periods of heavy traffic followed periods of little or no traffic. This is probably due to the signalized intersection in Cannon Falls, eight miles north of the intersection. To the south of the intersection, the closest town is Zumbrota Falls, but it does not have any intersections with US 52.

The traffic volume at the intersection varies based on the time of day. The traffic rate increases throughout the day until evening rush hour, then declines throughout the night until morning where it again begins to increase. The mean accepted gap showed a negative correlation with traffic volume. The mean gap was lowest during the evening rush hours and largest in the early morning hours.

Vehicles performing left and right hand turns had a higher mean gap than vehicles going straight through. This is expected as it takes more time to merge with traffic because the vehicle must accelerate to the speed of oncoming traffic.

Given our accepted gap definition, variation in accepted gap for various vehicle classifications was negligible. All vehicle classes had similar mean accepted gaps. The definition of accepted gap chosen for this report did not measure the time it took for the driver to act on their decision and to accelerate the vehicle into the intersection. Thus, vehicles with longer lengths and more mass (lower acceleration capabilities) actually selected larger gaps, but they ended up accepting similar risk as drivers of smaller vehicles.

Gaps accepted as a function of waiting time were also analyzed. When considering available gaps of 10 seconds or less, the gap accepted by a driver was relatively unaffected by the amount of time waiting at the stop bar, except for those drivers waiting between 17 and 25 seconds. Drivers waiting between 17 and 25 seconds took, on average, a gap 0.3 seconds smaller than the other drivers. For drivers waiting in the median, a slightly different trend was identified. When considering available gaps of 10 sec or less, drivers waiting from $0-10$ seconds accepted, on average, gaps of 7.1 seconds. However, drivers waiting more than 10 seconds accepted gaps of approximately 6.8 seconds.

Finally, weather conditions were cross-correlated with accepted gap. The mean accepted gap was lower for low visibility conditions than for high visibility conditions. Also, the mean accepted gap was lower for high precipitation rates. The speed of the main line vehicles decreased slightly during adverse weather conditions which may explain some of the larger gaps.

In order to measure the effectiveness of an IDS system a metric other than crash rate should be defined because crashes at one particular intersection are rare. Because the rural IDS system will
assist a driver with gap selection, reducing the number of poor gaps accepted (small gaps) is one metric that could indicate the system's effectiveness. To that end, the percentage of accepted gaps less than four seconds was found to be $3.2 \%$ of all accepted gaps. Reducing this number would indicate that drivers are accepting larger, and therefore, safer gaps. Of the small gaps, straight through maneuvers were over represented. Also, vehicles crossing/merging the southbound lanes of US 52 were also over represented with respect to gaps less than four seconds. The highest percentage of small gaps occurred with vehicles crossing the southbound lanes of US 52 from the median.

Next Steps. The next steps in the development the rural IDS system would be to collect data at more intersections to determine whether the driver behavior at this intersection is consistent with intersections of different configurations and in different parts of the country. This information will be valuable to the implementation of the DII. Once designed, the DII can be added to the surveillance system in a field operational test. Driver behavior metrics can be compared with pre-DII metrics to calculate the effectiveness of the system. If the system performs well, it would provide the traffic engineer with one more tool in the tool box to help reduce accidents.

## References

[1]. H. Preston, R. Storm, M. Donath, and C. Shankwitz, Review of Minnesota's Rural Intersection Crashes: Methodology for Identifying Intersections for Intersection Decision Support (IDS), Mn/DOT Final Report MN/RC-2004-31, St.Paul, MN 2004.
[2]. J.D. Chovan, L. Tijerina, J.A. Pierowicz, and D.L. Hendricks, Examination of Unsignalized Intersection Straight Crossing Path Crashes and Potential IVHS Countermeasures. Report DOT HS 808 152, DOT-VNTSC-NHTSA-94-2. Volpe National Transportation Systems Center, Washington, D.C., August 1994.
[3] J. Creaser, M. Rakauskas, N. Ward, J. Laberge, A simulator-based evaluation of smart infrastructure concepts of Intersection Decision Support (IDS) for rural thru-STOP scenarios. Project No. MN DOT 81655. Work Order 33. ITS Institute, University of Minnesota, Minneapolis, MN, 2005
[4] H. Preston, R. Storm, C. Shankwitz, and M. Donath, Wisconsin Rural Intersection Crash Analysis for Intersection Decision Support, Technical Memorandum, CH2Mhill, January 2005.
[5] V. Neale, M. Perez, Z. Doerzaph, S. Lee, S. Stone, Preparatory Analysis for the Cooperative Intersection Collision Avoidance Systems ITS Initiative, Final Report, Virginia Tech Transportation Institute, November 2004
[6]. A. Menon, A. Gorjestani, C. Shankwitz, and M. Donath, Roadside Range Sensors for Intersection Decision Support, Proceedings of the $7^{\text {th }}$ International IEEE Conference on Intelligent Transportation Systems, Washington D.C., September 2004, pp. 210-215
[7] A. Gorjestani, S. Bajikar, T. Pham, M. Donath, Evaluation of Radar for Snowplows: Initial Results, Technical Report, Minnesota Department of Transportation Office of Research Administration, St. Paul. MN, Final Report 1999-09, April 1998.
[8] B. Newstrom, Real Time High Accuracy Geospatial Database for Onboard Intelligent Vehicle Applications, Master's thesis, Mechanical Engineering Department, University of Minnesota, Minneapolis, MN, October 2000.
[9] A. Gorjestani, B. Newstrom, C. Shankwitz, and M. Donath, Advanced Range Sensor Processing Using DGPS and a Geospatial Database, Proceedings of the IEEE Conference on Intelligent Transportation Systems, ITSC ’01, Oakland, CA, August 2001.
[10] M. Sergi, B. Newstrom, A. Gorjestani, C. Shankwitz, and M. Donath, Dynamic Evaluation of High Accuracy Differential GPS, ION 2003 National Technical Meeting, Anaheim, California, January 2003.
[11] M. Sergi, A Virtual Mirror for Eliminating Vehicle Blind Zones, Masters Thesis, Mechanical Engineering Department, University of Minnesota, September 2002
[12] R. Ashworth, and C.G. Bottom, "Some observations of driver gap acceptance at a priority intersection", Traffic Engineering and Control, 18(12), pp. 569-571. (1977).
[13] American Association of State Highway and Transportation Officials, A policy on geometric design of highways and streets ( $4^{\text {th }} \mathrm{ed}$ ). Washington, DC: AASHTO. (2001).
[14] J. Darzentas, V. Holmes, and M.R.C. McDowell, "Driver behavior at a T-junction in daylight and darkness", Traffic Engineering and Control, 21, 1980, pp. 186-189.
[15] A. Polus, "Gap acceptance characteristics at non-signalized urban intersections", Traffic Engineering and Control, 24, 1983, pp. 255-258.
[16] D.W. Harwood, J. M. Mason, \& R.E. Brydia, "Design policies for sight distance at stopcontrolled intersections based on gap acceptance", Transportation Research Part A: Policy and Practice, 33, 1999, pp. 199-216.
[17] P. Soldbert, and J.C. Oppenlander, Lag and lag acceptances at stop controlled intersections, Highway Research Record, 118. Statistical and Mathematical Aspects of Traffic. Highway Research Board, Washington DC, 1966
[18] O. Adebisi, and G.N. Sama, "Influence of stopped delay on driver gap acceptance behaviour", Journal of Transportation Engineering, 115, 1989, pp. 305-315.
[19] A. Polus, "Gap acceptance characteristics at non-signalized urban intersections", Traffic Engineering and Control, 24, 1983, pp. 255-258.

Appendix A. EVT-300 Radar Performance

## Appendix A. EVT-300 Radar Performance

The Eaton-Vorad EVT-300 radar unit was selected as the primary range sensor for the IDS mainline system. This decision was based on a survey of presently available sensors and results obtained from other vehicle systems developed by the Intelligent Vehicles Laboratory at the University of Minnesota. In these previous projects ([7] and [9]) however, the sensor was only used as a vehicle-based sensor. The results of tests conducted to determine the feasibility of the EVT-300 as a roadside-based sensor are presented herein.

Two distinct types of tests were designed to evaluate the IDS surveillance system. The first type, a component test whose results are discussed in this section, uses a high accuracy DGPS system and probe vehicles to document sensor performance. The design of the IDS mainline surveillance system is based on these performance results.

A large scaled test was also conducted that evaluated the accuracy of the system in actual traffic conditions, and this system is also described in the next section.

## Experimental Setup

A single radar antenna unit was attached to a research grade mount equipped with a vernier turntable to adjust the radar orientation angle as shown in Figure 95. A riflescope was also rigidly mounted parallel to the antenna faceplate, so that it would rotate with the radar antenna. The riflescope was used to determine the radar yaw angle ( $\theta_{\mathrm{R}}$ ) with respect to North. A reference pole was placed 152 m away from the radar station and the positions for both the pole and the radar unit were measured using a highly accurate DGPS system. The riflescope was then used to align the radar along the line-of-sight with the pole. With both positions known, the yaw angle with respect to North was determined ( $\theta_{\mathrm{R}}$ in Figure 96). With this measurement, the vernier turntable could be zeroed, and further changes in the radar yaw angle could be measured using the vernier dial reading.


Figure 95. The EVT-300 Radar unit mounted on a Vernier Turntable.
The EVT-300 radar antenna was connected to a computer that collected the radar data (range, range rate and azimuth) at 10 Hz and processed the data to produce target position and velocity in state plane coordinates. This processed data was then sent to a data collection computer that added a timestamp before storing the data.

The probe vehicles (vehicles used as radar targets) were fitted with a high accuracy dual frequency, carrier phase DGPS receivers that provided position measurements with an accuracy of approximately 5 cm at 10 Hz [4]. A computer on a probe vehicle processed the DGPS data and then sent its position and velocity via wireless LAN to the data collection computer. A timestamp was added to each dataset to synchronize with the range sensor data. Figure 97 illustrates the probe vehicle experimental setup, and shows the experimental dataflow


Figure 96. Determination of the Radar Yaw Angle (w.r.t North)


Figure 97. Wireless data flow.
The probe vehicle receives a differential correction from the base station and computes its position using high accuracy dual frequency, carrier phase DGPS. This position is transmitted to the data-collection computer at the radar station


Figure 98. Signal Flow Diagram for the data-collection process
Synchronization of the data was done by grouping records within 58 ms of each other from the two data files. The 58 ms threshold used for the synchronization also takes into account the wireless LAN transmission lag (about 15ms). The timing diagram, and jitter, is illustrated in Figure 99 below.


Figure 99. Data Synchronization.
Data collected within 58 ms of each other were grouped together for analysis

## Experiment Parameters \& Objectives



Figure 100. Radar Geometries for a two-lane road

The independent variables for the experiment were:
Vehicle type: For IDS application, it is necessary to detect any type of vehicle on the road. Hence the tests were performed for two vehicles types to determine the effect on accuracy. A sedan and truck were used as probe vehicles for the experiment.

Speed: The probe vehicles traveled at two different speeds ( $40 \mathrm{~km} / \mathrm{hr} \& 72 \mathrm{~km} / \mathrm{hr}$ ) to determine the effects of speed on the sensor accuracy. Since the speed limit at the test track is $72 \mathrm{~km} / \mathrm{hr}$, the tests were limited to that speed.

Sensor Location: The sensor was placed at specified offsets from the two lanes ( $\mathrm{D}_{\mathrm{LC} 1} \& \mathrm{D}_{\mathrm{LC} 2}$ in Figure 100). The effect of the two lane-center offsets was determined. Measuring sensor sensitivity to location is necessary to justify the placement of items in the right-of-way adjacent to the road.

Sensor Orientation: Variations in road geometry and local right-of-way regulations will result in a variety of sensor orientations. To determine the sensor sensitivity to orientation, yaw angles were varied to determine the effect on sensor accuracy and coverage.

The experiment was designed to determine, for each independent vehicle type, the following measures of performance. In each case, the radar sensor measurement is compared to that provided by the DGPS system.

Lane Coverage: This is the length of a lane that can be covered by a single sensor. Figure 100 shows the theoretical lane coverage for two lanes ( $\mathrm{L}_{1 \mathrm{Cov}} \& \mathrm{~L}_{2 \mathrm{Cov}}$ ). The theoretical lane coverage was calculated using the manufacturer specified beam width of 12 degrees and a measured maximum sensor range of 134 m . Although the manufacturer specifies the maximum range to be 107 m , the sensor consistently detects the test vehicles to a 134 m range. The length of the line segment where the lane-center intersects with the edges of the theoretical radar beam is defined as the theoretical lane coverage. Lane coverage is essential to correctly determine the appropriate spacing between two radar stations placed along the road.

Lane Classification Accuracy: This is the ability of a vehicle position estimator to place the vehicle in the correct lane. Lane classification is dependent upon the error in the lateral position of the target as reported by the sensor (see Figure 101). For a standard sized lane (3.66m), a maximum lateral position error of $\pm 1.2 \mathrm{~m}$ allows a vehicle to be correctly associated with its lane of travel.

Lane Position Accuracy: This is the accuracy of the longitudinal position of the vehicle in the lane reported by the sensor as compared to the position reported by the DGPS system.

Speed Accuracy: Speed accuracy is critical for the IDS project because the future position of a target currently being detected has to be accurately estimated using velocity and acceleration, in order to accurately predict its time to the intersection.


Figure 101. Lateral \& Longitudinal Position Errors

## Experiment Results

Table 16 and Table 17 show the results of the experiments for the truck and sedan, respectively. DGPS data was not collected for the motorcycle. However, the lane coverage of the radar was determined for the motorcycle and was found to match that of the other two vehicles. The results described below also show that the accuracy of the sensor in terms of lane classification accuracy is better if the front of the vehicle is small. Furthermore, a longer vehicle produces a higher lane position (longitudinal) error. This means that for a motorcycle, the lane classification and lane position accuracy of the sensor should be higher than that for a passenger vehicle.

Theoretical lane coverage was determined by the geometry of the sensor orientation to the road and using a maximum sensor range of 134 m . It is assumed that the target returns from the sensor correspond to the center of the front of the target vehicle. This assumption, as shown later, is likely invalid; at this point it is not possible to determine the exact point on the target from which a radar return is received.

Table 16. Experimental results for a truck target

| No. | Sensor Distance to Lane Center (m) | Sensor <br> Orientation Angle w.r.t to Lane (degrees) | Theoretical <br> Lane Coverage (m) | Results |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  | Lane Coverage (m) | RMS Lane Classification Error (m) | RMS Lane <br> Position Error (m) | RMS <br> Speed <br> Error <br> (m/s) |
| $72 \mathrm{~km} / \mathrm{hr}$ |  |  |  |  |  |  |  |
| Run 1 | 4.25 | 0 | 90 | 115 | 0.33 | 6.7 | 0.13 |
| Run 2 | 7.9 | 0 | 52 | 105 | 1.03 | 7.58 | 0.28 |
| Run 3 | 4.25 | 3 | 105 | 124 | 0.43 | 7.15 | 0.26 |
| Run 4 | 7.9 | 3 | 80 | 96 | 1.15 | 7.63 | 0.31 |
| Run 5 | 4.25 | 6 | 113 | 120 | 0.7 | 8.01 | 0.33 |
| Run 6 | 7.9 | 6 | 94 | 114 | 1.17 | 9.7 | 0.32 |
| Run 7 | 4.25 | 9 | 79 | 96 | 1.12 | 10.64 | 0.33 |
| Run 8 | 7.9 | 9 | 103 | 105 | 1.75 | 11.58 | 0.29 |
| $40 \mathrm{~km} / \mathrm{hr}$ |  |  |  |  |  |  |  |
| Run 1 | 4.25 | 0 | 90 | 121 | 0.44 | 2.72 | 0.06 |
| Run 2 | 7.9 | 0 | 52 | 86 | 1.03 | 4.3 | 0.07 |
| Run 3 | 4.25 | 3 | 105 | 111 | 0.92 | 2.85 | 0.05 |
| Run 4 | 7.9 | 3 | 80 | 102 | 1.28 | 6.06 | 0.12 |
| Run 5 | 4.25 | 6 | 113 | 103 | 0.93 | 4.15 | 0.11 |
| Run 6 | 7.9 | 6 | 94 | 104 | 1.24 | 5.57 | 0.16 |
| Run 7 | 4.25 | 9 | 79 | 95 | 0.95 | 5.32 | 0.2 |
| Run 8 | 7.9 | 9 | 103 | 112 | 1.7 | 5.57 | 0.26 |

Table 17. Experimental results for a sedan target

|  | Sensor | Sensor | Theoretical |  | Results |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Dane Center <br> (m) | Orientation <br> Angle w.r.t to <br> Lane (degrees) | Lane <br> Coverage <br> $\mathbf{( m )}$ | Lane <br> Coverage <br> $\mathbf{( m )}$ | RMS Lane <br> Classification <br> Error (m) | RMS Lane <br> Position Error <br> (m) | RMS <br> Speed <br> Error <br> $(\mathbf{m} / \mathbf{s )}$ |
| $\mathbf{7 2 ~ k m / h r ~}$ |  |  |  |  |  |  |  |
| Run 1 | 4.25 | 6 | 113 | 115 | 0.77 | 3.17 | 0.23 |
| Run 2 | 7.9 | 6 | 94 | 111 | 0.96 | 3.94 | 0.48 |
| Run 3 | 4.25 | 9 | 79 | 96 | 0.96 | 4.29 | 0.25 |
| Run 4 | 7.9 | 9 | 103 | 105 | 1.39 | 4.54 | 0.67 |
|  |  |  |  |  |  |  |  |
| $\mathbf{4 0}$ km/hr |  |  |  |  |  |  |  |
| Run 1 | 4.25 | 6 | 113 | 117 | 1.29 | 1.11 | 0.09 |
| Run 2 | 7.9 | 6 | 94 | 102 | 1.3 | 2.4 | 0.14 |
| Run 3 | 4.25 | 9 | 79 | 105 | 1.58 | 1.22 | 0.5 |
| Run 4 | 7.9 | 9 | 103 | 112 | 1.56 | 3.33 | 0.91 |
| Run 5 | 7.9 | 16 | 27 | 43 | 3.8 | 1.83 | 0.81 |
| Run 6 | 26.7 | 16 | 61 | 62 | 1.95 | 8.56 | 0.68 |

The experiment was conducted with the sensor placed at one position and the probe-vehicles traveling in two different lanes. The distance of the sensor from each of the two lane centers was 4.25 m and 7.9 m .

Sensor orientation was varied between 0 and 9 degrees with intervals of 3 degrees for the truck. Similar experiments were conducted with the car, with an additional test at 16 degrees to determine the sensor sensitivity to the wide angle.

Two sets of data were collected for each condition and the tabular results are the average of the two data sets. The RMS values in Table 16 and Table 17 were calculated using EACH of the two data sets for each condition. The data used for RMS calculation covered the time the probevehicle was first seen by the sensor until the time at which the target moved out of the field of view of the sensor. An average of 47 data points were collected for the runs at $72 \mathrm{~km} / \mathrm{hr}$ and 91 data points at $40 \mathrm{~km} / \mathrm{hr}$.

The following can be concluded from the data:
The actual coverage is consistently larger or matches the theoretical lane coverage (see Figure 102). The length of the line segment where the lane-center intersects with the edges of the theoretical radar beam was considered as the theoretical lane coverage (See $\mathrm{L}_{1 \text { Cov }} \& \mathrm{~L}_{2 \text { Cov }}$ in Figure 100). Because the actual coverage matches the theoretical coverage, the theoretical coverage can be used to determine sensor locations for an actual intersection.

The results for the sedan (Table 17) show that the lane coverage is similar to that for the truck. The maximum lane coverage for both lanes occurs when the sensor orientation angle is between 3 and 6 degrees.

Lane classification accuracy decreases as the orientation angle ( $\alpha$ in Figure 102) relative to the road increases. Lane classification accuracy also decreases for increasing sensor distance from the lane (Figure 103). In all the data sets except one, the RMS error was well under 1.2 m , the requirement for accurate lane classification. At a distance of 8 m from the lane center and at an orientation angle of 9 degrees, the lane classification error was larger than the 1.2 m threshold; this arrangement should be avoided.

The results for the sedan show that the lane classification error is slightly lower than that for the truck. This is likely due to a more narrow vehicle cross section


Figure 102. Sensor coverage at various sensor orientations (Truck at $72 \mathbf{~ k m} / \mathbf{h r}$ )


Figure 103. Lane classification error at various sensor orientation angles
c. Lane position accuracy also decreases with increase in orientation angle and sensor distance to the lane. A substantial difference exists in the lane position accuracy for the different vehicles. The truck produced a significantly larger lane position error than did the sedan. This can be attributed to the fact that the truck is longer than the sedan. As the orientation angle increases and the distance from the sensor to the lane increases, more of the side of the vehicle is visible to the sensor; so the target is likely detected at the sides. Lane position error was also higher at $72 \mathrm{~km} / \mathrm{hr}$ than it was at $40 \mathrm{~km} / \mathrm{hr}$. This may be attributed to an internal radar-processing lag.
d. The speed accuracy of the radar was found to be very good. However, as shown in Figure 104, this error also increases with increase in both radar orientation angle and distance to the lane center. For the IDS project, because the position of a target presently detected has to be projected to determine its time to reach the intersection, it is critical that the speed accuracy be high so that an accurate estimate of the target position can be made. Hence the orientation angle and distance to lane must be kept as low as possible.

The effect of vehicle size on the accuracies was negligible. The only significant error difference was in the longitudinal position (lane position accuracy). As mentioned earlier, this could have been caused due to radar beams hitting the sides of the vehicle.


Figure 104. Speed Error at various sensor orientations for two different lanes
The results from the tests conducted with the EVT-300 verify the fact that the sensor can be used as a roadside range sensor. These experiments were critical in the design stage of the intersection, where sensors had to be laid out for the mainline coverage.

Appendix B. Virginia Tech Transportation Institute Research on Point Sensors

## Appendix B. Virginia Tech Transportation Institute Research on Point Sensors

The Virginia Tech Transportation Institute, as part of the IDS and ICAV (Intersection Collision AVoidance) projects, performed a comparison of point detection sensors and continuous detection sensors. Several algorithms were developed to detect signal violators and simulations were run with both point detection sensors and continuous detection sensors. In the case of the point detection sensors, the speed of the vehicle was measured at a given distance from the intersection.

A variety of distance threshold settings were tested from 100ft (30.5m) to 250 ft ( 76.2 m ) in 5 ft $(1.5 \mathrm{~m})$ steps, and vehicles speeds varying from $25 \mathrm{mph}(40.2 \mathrm{~km} / \mathrm{h})$ to $50 \mathrm{mph}(80.5 \mathrm{~km} / \mathrm{h})$ with $0.5 \mathrm{mph}(0.8 \mathrm{~km} / \mathrm{h})$ steps. Figure 105 shows a plot with the percentage of drivers that stop and go through for the above ranges and range rates. It can be seen that at speeds between 40 mph and 47 mph , the decision uncertainty stretches between 150 ft and 250 ft from the intersection. This clearly shows that at this section, continuous coverage is required.


Figure 105. Percentage of drivers based on stop decision

Further work using speed detection at a fixed distance from the intersection shows that far more violators would be missed by just using point sensors. Figure 106 shows the plot with missed violators in the simulation study for both single-point sensors and continuous detection sensors.


Figure 106. Missed violators with single-point detection sensors and continuous detection sensors (Simulation results)

The study found that for a vehicle traveling at 45 mph , if a 0.5 g deceleration rate and a one second RT was assumed, then the critical point is about 150 ft ( 45.7 m ) away from the intersection. At this point a trigger at $44 \mathrm{mph}(70.8 \mathrm{~km} / \mathrm{h})$ would result in an $11 \%$ false positive (FP) classification (incorrectly classified as a violator) and an $11 \%$ false negative (FN) classification (incorrectly classified as a 'stopper'). In order to reduce the percentage of FN, a trigger at a speed of $38 \mathrm{mph}(61.2 \mathrm{~km} / \mathrm{h})$ would reduce the FN to $0.5 \%$, but the FP drastically increases to 50\%.

An analysis was also performed using multiple point sensors, and it was found that the performance could match continuous detection sensors, if a sufficient number of point sensors were used. The performance quickly degraded as fewer sensors were used. Table 18 lists out the requirements for multi-point sensors for the five algorithms developed. The method used estimated the areas of the intersection where locating sensors would be most useful, which was algorithm type specific, and located various sensor densities in these areas, testing for increases in the number of false alarms and misses. Some algorithms were not amenable to the use of multi-point detection and these instances are noted in the table.

Table 18. Multi-point detection sensor requirements

| Algorithm | Multi-point detection requirements |
| :---: | :---: |
| Case 2: Basic kinematics, deceleration | 35 mph : Detectors placed every 5 ft from 95 to 155 ft from the intersection. <br> 45 mph : Detectors placed every 10 ft from 120 to 220 ft from the intersection. |
| Case 3: Parameterized kinematics, deceleration | 35 mph : Not recommended <br> 45 mph : Detectors placed every 10 ft from 120 to 220 ft from the intersection. |
| Case 6: Dual threshold | 35 mph : Not recommended <br> 45 mph : Not recommended |
| Case 7: Inverse TTI | 35 mph : Not recommended <br> 45 mph : Detectors placed every 10 ft from 120 to 220 ft from the intersection |
| Case 8: Point detection of acceleration | Already based on point detection, no further research needed. |

Appendix C. Point Sensor Analysis: Case Study of Minnesota Test Intersection

## Appendix C. Point Sensor Analysis: Case Study of Minnesota Test Intersection

To determine the viability of point sensors for mainline surveillance, a study was undertaken to determine errors associated with estimating vehicle trajectories using data from point sensors. Radar data was used to provide an array of virtual point sensors at the Minnesota test intersection. A plan view of the virtual sensor locations and the intersection geometry are shown in Figure 107 below.


Figure 107. Diagram of mainline leading to crossroads at Minnesota Test Intersection. Analysis is performed for point sensors assumed to be placed at locations A-E above.

Existing radar sensors were used to simulate points sensors by providing mainline vehicle speed and lane of travel only at points A-E above. At each of these points, the vehicle speed and lane of travel measured by the radar were used to project the time at which that vehicle was expected to reach the intersection crossroads.

The estimated time at which the vehicles reached the crossroads from points A-E above were compared with actual trajectories tracked by the full coverage surveillance system. As is
expected, errors from points furthest from the intersection created the largest trajectory estimation errors. These errors were compounded by vehicles using the turn lanes (turn lanes begin at location B ) because of the reduced speeds used by vehicles in the turn lanes.

Graphs of these errors are shown in Figure 108 and Figure 109 below.


Figure 108. Histograms of trajectory estimation errors from intersection locations A, B, D, and $E$ for vehicles not making turns onto the minor road.

The plots in Figure 108 show relatively low variance in speed profiles for vehicles on the mainline. However, a significant number of errors greater than one second occur from estimations based at locations D and E. This one second error represents fifteen percent of an acceptable gap of seven seconds, which may prove to be excessive. This will be studied further in a follow-on project.


Figure 109. Histograms of trajectory estimation errors from intersection locations A, B, D, and $E$ for vehicles making turns onto the minor road.

The plots in Figure 109 show significant variance in speed profiles for vehicles on the mainline. This is due to the fact that vehicles typically decelerate before entering the intersection turn lanes. Clearly, to produce timely, credible warnings, trajectory estimation errors of greater than one second should be avoided. Only arrays of point sensors are capable of providing greater accuracy; however, the installation, maintenance, and operations cost of multiple point sensors is likely to be significantly higher than that for a sensor providing a coverage area.

It is unlikely that point sensors will play a significant role in reducing the complexity of the mainline sensor suite. However, with the low variance in mainline traffic speed for vehicles not turning, opportunities do exist to reduce the number of sensors needed to track traffic. A reduction in sensor numbers will require a greater reliance on trajectory estimation techniques and software. This tradeoff will be investigated through the course of the follow-on project.

## Appendix D. Intersection Decision Support Design Guide

## Appendix D. Intersection Decision Support Design Guide

## 1. Introduction

This document is meant to be a guide to the design of an instrumented intersection between a high volume expressway and a low volume road. The instrumentation will be used to monitor the movement of traffic and collect driver behavior data. In this introduction we will give a brief description of the system and the purpose that it has been designed for. The following chapters contain more specific details of a typical installation. The information given here is the result of experience gained in the construction and operation of such an intersection at Minnesota Highway 52 and Goodhue County Road 9 in southern Minnesota.

The instrumentation consists of 14 radar sensors covering approximately $1 / 2$ mile of the main highway in each direction. Additional instrumentation includes 4 visible light and 2 infrared video cameras mounted on $35-\mathrm{ft}$. surveillance poles, 4 scanning laser rangefinders for vehicle classification and 2 more radar sensors covering traffic approaching on the minor road. Each of these sensors is connected to a small data collection computer mounted close to it that is in turn connected to a larger computer in a central cabinet where the data is stored on removable hard disk drives. There is also a power distribution system to supply 120 VAC to all the remote cabinets and a DSL data connection to allow remote monitoring of the system.

The purpose behind this installation is to gather data that can be used to design a Driver Intersection Interface (DII) that will assist drivers on the minor road as they attempt to enter or cross the dense, high speed traffic on the mainline. This is a scenario that is causing a huge number of accidents across the country. There is evidence that a significant percentage of these accidents happen when drivers on the minor road make a poor choice of the gap in mainline traffic as they attempt to negotiate the intersection.

The first step in designing a solution to this problem is to collect data on traffic movements at an intersection that has been shown to have a high accident rate and that is what this system is designed to do. The radar sensors along the mainline record the positions and velocities of traffic on the mainline and the computers that analyze radar data calculate the size and location of gaps between vehicles. The radar and laser sensors along the minor road are used to classify vehicles into different sizes (motorcycles, passenger cars, light trucks, heavy trucks and buses, etc.) and track their movement through the intersection. The cameras on surveillance poles are used to keep track of vehicles in the middle of the intersection where other sensors cannot be installed.

With these sensors and the included data processing capabilities we are able to collect statistics on the way that drivers move through the intersection and the gaps that they select. An analysis of the collected data should provide insights into the design of a future sign or signal (the DII) that will help prevent accidents at this type of intersection.

A schematic diagram showing the layout of the central part of an instrumented intersection with a DII installed is shown in Figure 110. For a permanent installation a wired communication setup is preferred. We are also planning a portable system that would use the wireless communication option also shown in Figure 110.


Figure 110. Instrumented intersection schematic showing the location of the minor road vehicle classification sensors, some of the mainline radar sensors and the eventual driverintersection interface (DII).

Figure 111 and Figure 112 on the following page show the overall wiring diagram for the system installed in Minnesota. The rest of this manual will fill in the details for each of the different parts of the system: the radar stations, the laser scanner stations, the video camera stations, the main computer cabinet and the power distribution system.


Figure 111. Cabling schematic for southbound lane.


Figure 112. Cabling schematic for northbound lane.

## 2. Mainline Sensors

### 2.1. Roadside Radar



Figure 113. Roadside radar installation.
On Minnesota's Hwy 52 installation there are seven radar stations on each side of the mainline and one more on each minor road approach for a total of 16 radar sensors. The radar stations on the mainline are spaced approximately 400 ft . apart with five stations upstream of the intersection and two more downstream. The minor road sensors are placed approximately 150 ft on either side of the mainline. Curves or hills will increase the number of sensors required. The overall layout of a typical radar station is shown in Figure 114.


## Figure 114. Radar station details.

The radar sensors are Eaton Vorad EVT-300 units commonly used as mobile radar systems in the trucking industry. They are mounted on 3 lb . flanged channel sign posts driven approximately 4 ft . into the ground as shown in Figure 113. These posts are installed 12 ft from the edge of the road shoulder. In Minnesota this is the same distance from the road as other highway signs. The farther away from the road that the radar sensors are mounted the less accurately they will measure speed and position. Due to the proximity to the traveled lanes the power and data connections to the radar include a breakaway electrical connector. The radar is mounted to the post with a bracket (Figure 115 and Figure 116) that allows the sensor to be aimed horizontally into the traffic flow. The bracket should be mounted at a height that positions the radar sensor approximately 18 inches above the surface of the traveled pavement. At Mn /DOT's suggestion we added a reflector to the top of each post.

The radar is powered by a low voltage ( 7.3 volt) power supply in the nearby computer cabinet described in the next section. Radar data is transferred to the computer cabinet through a serial J1708 connection. The low voltage power and the J1708 data are carried by a four conductor 16 gage cable routed through a 1" heavy wall rigid PVC Schedule 80 plastic conduit that runs from the radar post to the computer cabinet


Figure 115. A simplified radar sensor mounting bracket


Figure 116. Radar sensor mounting bracket.

### 2.2. Roadside Radar Processor



Figure 117. Roadside radar processor station.
Each radar sensor requires a power supply and a data collection computer. These are mounted on another 3 lb . flanged channel sign post located near the radar sensor but at a convenient and safe distance farther from the traveled roadway. In Minnesota this should be at least $35-\mathrm{ft}$. from the road. This post may have to be extended vertically to make room for a computer cabinet, a circuit breaker box and the power junction box. Due to the extra size of the cabinets mounted on this post it was reinforced by second angled post as shown in Figure 117.

The computer cabinet is a NEMA 420 " x 16 " x 10 " enclosure. Specifically we used Wiegmann NEMA 4 single-door wall mount enclosures ordered from Automation Direct (www.automationdirect.com) as their part \#N4201610. We added a sub-panel assembly (part \#NP2016) and made a 90 degree bend in it to make a shelf to hold equipment inside. A padlock should be provided to secure each cabinet.

There are three main pieces of equipment in this cabinet: a custom interface and power supply box for the radar, a PC-104 computer and an Ethernet extender. Figure 118 shows the inside of this cabinet and Figure 119 shows components and data flow.


Figure 118. Radar station computer box with circuit breaker box below.
The radar interface box contains a data converter and a power supply for the Eaton Vorad EVT300 radar sensor. The data converter, a model J1708P1 from B\& B Electronics, takes the J1708 data stream from the radar and converts it into an RS-232 format to be read by the data collection computer. The power supply consists of an ICP Electronics Inc. model ACE-855A12-volt dc supply and a separate voltage regulator circuit that drops the voltage to 7.3 volts as required by the EVT-300. There is also a small 12 -volt cooling fan mounted in the box. A block diagram of the radar station equipment connections is shown in Figure 119.


Figure 119. Radar station equipment connection schematic.
The radar data acquisition computer is an Octagon Systems model 2050 PC-104 platform with Ethernet and Compact Flash. The computer is contained in a modular aluminum enclosure based on Parvus PRV-0802A-02 components.

The distance between the radar stations and the main computer cabinet where data is stored is typically longer than a standard Ethernet connection will reach so we have installed Patton Model 2168 CopperLink 16.7-Mbps Ethernet Extenders at the radar station computers and in the main cabinet. We used standard CAT 5 plenum cable in heavy wall rigid PVC Schedule 80 plastic conduit to make the connection.

There is a surge protected power strip plugged into a 120 -volt 15 -amp outlet mounted in the enclosure.

Mounted on the post below the computer cabinet is a standard outdoor circuit breaker box with a $120-\mathrm{VAC}, 15-\mathrm{amp}$ circuit breaker for the equipment at that station. Below the circuit breaker box is a power splice box where 120 VAC power is tapped from the distribution lines. This box is a model T1220 from Midwest Electric Products. These two boxes are shown open in Figure 120.

To facilitate pulling wires through the long conduit runs there is a handhole located near each radar station and one at each end of the conduits that were bored under roadways. We used PVC handholes as per Mn/DOT standard plate 8144A.


Figure 120. Typical circuit breaker and power splice boxes at radar and laser scanner stations.

## 3 Minor Road Sensors

### 3.1 Roadside Laser



Figure 121. Vertical and horizontal roadside laser scanners.
There are four laser scanners used to classify vehicle size on the minor road. On each side of the major highway there is one scanner mounted horizontally to measure vehicle length and one mounted vertically to measure vehicle height. These sensors are model LMS221 30206 (Order \# 1018022) with heat and fog compensation from SICK Inc. They are mounted on 3 lb . flanged channel sign posts with a reflector on top using a bracket as shown in Figure 122. There is a180 degree dust prevention shield (SICK part \# 4030559) mounted around each scanner. These sensors are also placed 12 ft . from the shoulder and therefore require breakaway electrical connectors. The horizontal scanners are mounted 18 in. above the elevation of the traveled lane. The vertical scanners are mounted 3 ft . above the elevation of the traveled lane. In some cases, as in the left part of Figure 121 there will also be a radar sensor mounted on the same pole.


Figure 122. Laser scanner mount.

### 3.2 Roadside Laser Processor

The power supplies and data collection equipment for the laser scanners are mounted on another nearby pole in a manner similar to the radar processing equipment described in the previous section on radar stations. The equipment enclosure is larger for the laser stations than for the radar stations. We used Wiegmann NEMA 424 " x 20 " x 10 "single-door wall mount enclosures (part \# N4242010 from Automation Direct with subpanel part \#NP2420.) The subpanel was bent at a right angle to make a shelf as in the radar station cabinets.

The computers for the laser scanners are Octagon Systems model PC-770 PIII's with a PC-104 to PCI converter card from Douglas Electronics Inc. (part \# 6-DE-65/104 RS C). The PCI converter card accommodates a PCI interface card for the laser scanner (SICK part \# 60222515). The power supplies for these computers are the same ICP America Inc. model \# ACE-855A's that power the radar station computers. The power supplies for the laser scanners are 24 volt, 150 watt model number PSS-150-24 manufactured by Wall Industries. Patton Model 2168 CopperLink 16.7-Mbps Ethernet Extenders are used to send the data to the computers in the main cabinet. There is also a surge protected power strip plugged into a 120 -volt 15 -amp outlet mounted in the enclosure.

Mounted on the post below the computer cabinet is a standard circuit breaker box with a 120VAC, $15-\mathrm{amp}$ circuit breaker for the equipment at that station. Below the circuit breaker box is a power splice box where 120 VAC power is tapped from the distribution lines. This box is a model T1220 from Midwest Electric Products.


| Cabinet Parts List |
| :--- |
| 1. Nema Cabinet |
| a. Sensor Computer |
| b. Ethernet extender |
| c. 120 VAC Outlet |
| d. 24 VDC power supply |
| e. lock for cabinet |
| f. 120 VAC cable |
| g. ethernet cable |
| h. Surge-protected power strip |
| i. Cooling fan |
|  |


| Cabinet Parts List cont'd |
| :--- |
| 2. Electrical Junction Box |
| a. Box |
| b. Circuit Breaker |
| c. Conduit down to direct bury |
| i. power |
| ii. ethernet |
| 3. Post |
| a. post, 3\# or 4\# hardware |
| b. bracket for cabinet |
| c bracket for electrical junction box |
| d. conduit between junction box and |
| cabinet |
| e. conduit down to direct bury vault |

Figure 123. Camera equipment cabinet schematic and parts list.


Figure 124. Typical laser sensor station layout.

## 4. Crossroad Vision Sensors

### 4.1 Camera Mast



Figure 125. Lowerable camera pole.
Millerbernd Manufacturing Co. of Winstead, MN supplied 35-ft. tall self-lowering camera masts (Figure 125). These masts are hinged and have an internal hand operated winch that raises and lowers the top portion to facilitate the installation and maintenance of cameras. We used Millerbernd Type 1 single camera mount tops and fabricated our own attachments for multiple cameras when necessary (Figure 126).


Figure 126. Camera enclosures and mounts. Pole has been lowered for access to cameras.

The foundations for these poles were constructed as Design E Light Pole Bases as detailed in Mn/DOT standard plate \# 8127B
(http://www.dot.state.mn.us/tecsup/splate/english/e8000/s8127b.pdf).
Basically this design specifies a $2-\mathrm{ft}$. diameter by 6 -ft. deep concrete cylinder with 1 -in. diameter threaded anchor rods to attach the camera pole. As shown in the Mn/DOT standard plate PVC conduit is embedded in the concrete to permit below grade entry of electrical cables. To attach an electrical cabinet we built a simple steel frame that bolts to the concrete base as shown in Figure 127.


Figure 127. Camera electrical cabinet and base.

### 4.2 Cameras and Enclosures

All four camera stations have visible light cameras. The two stations nearest the intersection also have infrared cameras to track cross traffic at night. The four visible light cameras are Panasonic WV-BP330 high-resolution 120VAC B/W cameras with L212VDCP Rainbow 2.7 mm to 12 mm auto iris vari-focal lenses. These cameras are mounted inside Pelco EH3512-1 120 VAC outdoor hinged lid enclosures with heater/defrosters added. Video signals are amplified with Inline/Extron IN3212 1x2 video distribution amps mounted in the cabinet at the base of the mast.

There are two different models of infrared cameras. Both cameras are manufactured by ThermoVision and were purchases from FLIR Systems Inc. One IR camera is a model A20VComposite with a sensitivity of minus $20^{\circ} \mathrm{C}$ to $250^{\circ} \mathrm{C}$. This camera has a keyboard interface, an AC power supply and a $25^{\circ}$ field of view lens. The other camera is an A40V-Composite with a sensitivity of minus $20^{\circ} \mathrm{C}$ to $500^{\circ} \mathrm{C}$ and features a $320 \times 240$ uncooled microbolometer detector. This camera also has a keyboard interface and an AC power supply. We have three lenses for
this camera: the standard $24^{\circ} \mathrm{FOV}$, one $45^{\circ} \mathrm{FOV}$ and one $80^{\circ} \mathrm{FOV}$. Both IR cameras are mounted inside Pelco model EH5723 outdoor hinged lid 120V enclosures with the optional heater /defroster and EH5723 sun shrouds. The windows in these enclosures must be replaced with polyethylene sheeting that is transparent to infrared radiation. We used translucent sheeting from Edmund Scientific (part \# NT32-806).

To enhance the image detected by the infrared cameras we added an infrared illuminator to one camera pole. This illuminator is manufactured by Extreme CCTV Inc. as model number ZXLED850.30 using their SuperLED technology.


Figure 128. Camera equipment cabinet schematic.


Figure 129. Typical camera pole installation.

## 5. Main Controller Cabinet

### 5.1 Cabinet Details



Figure 130. Main computer cabinet.
The main controller cabinet is where all remote sensor data is collected and stored on removable hard drives. The cabinet itself is a model 334 equipment cabinet from Brown Traffic Products. The cabinet includes the following accessories: a cage assembly, a fan panel, a drawer assembly, two equipment shelves and a two fluorescent lamp assembly.

This cabinet is mounted on a 16 " thick concrete slab as per Mn/DOT standard plate 8119C and sits next to the power distribution cabinet that is described in the next section.


Figure 131. Main computer cabinet and schematic.
There are four computers installed in the main cabinet. The main control computer is used to analyze sensor data and keep track of vehicle location and gap sizes, etc. Another computer is connected to the video cameras and is used for image processing. There is one computer dedicated to storing data on removable hard drives. The fourth computer is connected to a DSL router and is used as a web server to allow off site access to the system.

The main control computer was ordered from CyberResearch Inc. and consists of their CPCV COP-1400 PIII single board computer, a DIMM 256-133 memory module, an LBJ6 rackmount chassis, a MSI 01055-B floppy disk drive, a PB2PR05P4x passive backplane and a PWR 925A power supply. There is also a 15" LCD monitor/keyboard/mouse/speaker from ArmorLink Corp. (their part \# LKM-9268AB-EN with cable set \#LKM-CB18A) that can be switched between any of the installed computers.

The other three computers, one for image processing, one for data storage and one used as a web server are all similar. They were ordered from ArmorLink Corp. and consist of the following parts: a SAGP-865EVG (533MHz FSB) single board computer, a RACK-2000B computer chassis with an AE-840A power supply, a PCIAGP-5SD backplane, a CF-512 CPU cooler, a 2.4Ghz Intel P4 processor, an ASUS 9520-TD 128MB GeForce FX5200 graphics card, 1GB of memory (Kingston KVR333X64C25K2/1G), a Seagate Barracuda 80GB ST380011A hard drive and another Seagate200GB ST320082A hard drive. The 200GB drives are mounted in StorCase DE110 Ultra ATA/133 HH Frame + Cable-less LP Carriers (StorCase Technology part number

S21B100 for 5.25" drives and S21B102 for 3.5" drives) to make them easy to remove to transfer data back to the lab.

The main cabinet also contains 24 Patton model 2168 CopperLink 16.67-Mbps Multi rate Ethernet extender rack cards (Patton \# 2168RC/L) to receive sensor data from remote sensor stations. These cards are mounted in a Patton high-density 2 U rack assembly with redundant power supplies (Patton \# 1001R14P/RUI). There are also two GarrettCom 6K16V Ethernet switches in the cabinet.

There is also a Trimble Acutime 2000 Synchronization kit that provides an accurate time base for the system. This kit consists of an Acutime GPS smart antenna, a synchronization interface module and associated cables and software.

There are 12120 VAC surge protected outlets provided in the cabinet.
Figure 131 shows the layout of equipment installed in the main computer cabinet.

## 6. Power Distribution Cabinet

### 6.1 Cabinet Details



Figure 132. Main electrical power cabinet.
The main electrical cabinet is a Mn/DOT Type L2 lighting service cabinet with 2-100 amp 2pole main circuit breakers and 16-20 amp single pole branch circuit breakers. The inside of this box is shown in Figure 133 and a wiring diagram in Figure 134.


Figure 133. Inside of main electrical cabinet.


Figure 134. Power cabinet wiring diagram.

Appendix E. Prototype License Plate Reader System

## Appendix E. Prototype License Plate Reader System

The IDS Surveillance system was designed to collect macroscopic gap acceptance data. For this application, macroscopic analysis allows gap acceptance to be described as a function of vehicle classification, time of day, season, and weather conditions. Driver age was not included as part of the macroscopic data set. Crash analyses, literature searches, and simulator research have indicated that older drivers are over-represented in rural intersection crashes. This motivated the addition of a measure of driver age to the set of macroscopic data collected at the intersection.

License plate information was determined to be a surrogate measure of driver age. Because "older" is considered to be an age above 65, the correlation between registered driver's age and the age of the actual driver is expected to be high. This is primarily for two reasons. First, gender has been shown to be weakly correlated to gap acceptance problems; older female drivers are as likely as older male drivers to have a gap acceptance related crash. Second, older drivers are unlikely to have their vehicles driven by their children; the likelihood that the age of the owner of the registered vehicle is close to the age of the driver of the vehicle determined to be at the intersection is high.

A number of commercial-off-the-shelf (COTS) license plate reader systems were investigated to determine the relative appropriateness to this application. COTS license plate reading systems can be generally classified as either toll enforcement or red-light running enforcement. Toll enforcement systems typically use a camera mounted on an overhead gantry to capture license plate information; red-light running systems use an array of ground-based cameras to capture license plate readers. Toll control systems use both the DOT installed illumination at toll stations (which improve ambient light conditions) and camera flash lighting to capture a readable image. Red light running systems also use flash lighting to enhance captured images. Both of these applications allow a camera to be mounted close to the vehicle longitudinal axis, allowing the CCD or image capture element to be approximately parallel to the license plate.

Both classes of systems were considered for this application. These systems typically use VGA/XVGA video-camera based image capture systems to collect video data, and an automated character recognition system which processes the captured image and produces a computer file which contains the license plate data information.

The four leading system vendors, SYS4S, CIVICA, VEGA, and PIPS, were contacted and asked to provide a system recommendation and price quotation. Prices ranged from $\$ 9500$ to $\$ 18,000$. The less expensive systems generally require an annual maintenance and license fee; the more expensive systems incur no such annual fees.

Although system recommendations and quotes were provided, no vendor was willing to demonstrate their system on-site at the Minnesota test intersection. The alignment of the Minnesota test intersection puts the license plate reading cameras off of the longitudinal axis of the vehicle, which adds a perspective view to the image. Second, camera flash lighting cannot be used as the goal is to capture the license plate of every vehicle approaching the minor road. Camera flash lighting would disturb both mainline and minor road traffic. Third, these license plate reading systems are designed to operate under conditions where the ambient lighting is present, either naturally (i.e., street lights) or because of the application (flood lighting at toll
stations). The rural environment as the Minnesota test intersection presently has no street lighting, and flash lighting is unacceptable as it will cause driver distraction. Because of the lack of control over lighting conditions, vendors likely felt that their chances of success in this application were low. Although they were requested, no vendor would provide an on-site demonstration of their system or technology.

Because of the unwillingness of any vendor to provide an on-site demonstration of their system, the ability of any vendor to provide a robust solution was questioned. A cheaper prototype system was developed to determine whether a more expensive system was likely to work, or even perform better than available systems (for this application).

The prototype system developed by the IV Lab consisted of a 5 mega-pixel camera with two particular modifications:

- Infrared blocking filter removed to provide higher sensitivity to infrared light.
- A remote shutter activation system which would allow a computer to command a camera exposure.

A camera was procured, modified for this application, and installed in a weatherproof case. The camera and an infrared illuminator were mounted on the stop-sign on the east side of Minnesota test intersection. A photo of the installation is shown below in Figure 135. The system uses an IR illuminator to improve lighting during nighttime operation.

A command to trigger the camera is provided from a laser-station computer; the time at which the command is issued is based upon vehicle position as measured by the minor road laser scanner and radar. When the front of the vehicle is determined to be in the desired position, the trigger signal is sent to the camera. When the trigger signal is received, the camera computes its required exposure (shutter speed and aperture settings), opens the shutter, and captures its image. The rate at which a camera can capture an image depends upon lighting conditions and the power of the microprocessor controlling the camera. The capability of the camera microprocessor has limited the success of this prototype system. Under many conditions, the camera takes too long to determine the proper exposure; this allows a vehicle to pass through the optimal location needed to read a license plate, resulting in lost license plate data. This problem occurs primarily during twilight and nighttime exposures.

The camera on-board, removable flash memory holds 4GB of images, or approximately one month of minor road traffic. U of MN personnel will travel to the intersection, remove the flash card from the camera, burn the images to a laptop, reformat the 4 GB flash card, and reinstall it in the camera in the intersection. This will be performed during routine visits for data collection (i.e., the removable harddrives from the intersection are replaced periodically as they become full).

Once images are transferred to the laptop, they are brought to the IV Lab for archival and postprocessing. Post-processing consists of a human scrolling through images, and recording license plate data, date, and time of day information in a spreadsheet. Once the data is collected, the information in the spreadsheet can be used to query the Minnesota DPS vehicle registration
database to determine the age of the registered owner of the vehicle whose license plate was recorded.

For a first attempt, the system worked reasonably well. Part of the success of the system can be attributed to the high resolution of the images captured. The resolution of the 5 mega-pixel camera (approximately $3000 \times 1700$ pixels) is six times greater than the XVGA image ( $1024 \times 768$ pixels). This high resolution allows the image to be enlarged to better facilitate the reading of the license plate image. A visible light filter is added to the camera lens to minimize the effect of visible light of headlights on the exposure when vehicle headlights are turned on.


Figure 135. Prototype license plate reader system at Minnesota test intersection. IR illuminator is always active. IR Camera shutter is triggered remotely based on vehicle position determined by minor road laser scanners and radar. Images are stored on 4 GB flash memory. This flash memory provides approximately one month of image storage.

Daylight, twilight, and nighttime images are provided below. Daylight photos are generally good, with the license plate easily discernable approximately $90 \%$. (See Figure 136 below.) Twilight pictures result in acceptable exposures approximately 33\% of the time (See Figure 137
and Figure 138 below.). Nighttime pictures are legible in approximately $25 \%$ of the exposures taken. (See Figure 139 and Figure 140 below.)

Three issues prevent the system from operating at a higher level. First, length of time between the command to open the shutter and the time it took to finally open the shutter was quite variable. The camera used in this application was a fixed focal length, range finder camera. Although high resolution, these "point and shoot" cameras suffer from poor shutter command response. A camera with higher computational power would allow a higher percentage of exposures with vehicles in the proper location

Second, the camera used in this prototype is fixed focal length, with a relatively wide angle lens. A camera with a zoom lens would allow an exposure with a less acute angle between the camera and the license plate by releasing the shutter at a greater distance from the camera. Third, the illumination system could be improved. Better shutter control and a less acute approach to the camera creates the opportunity for an IR illuminator which is biased toward a spot light instead of a flood light.

In terms of cameras, a professional-level digital IR single lens reflex (SLR) camera with a zoom lens will be used in the second phase. The IR illumination system will be improved as well.


Figure 136. Typical image captured by license plate camera during daylight hours at the Minnesota test intersection.
Not only are license plates readable, but the system offers insight into complicating factors. This driver is talking / listening to his cell phone.


Figure 137. Typical twilight exposure, occurring approximately $2 / 3$ of the exposures. Blurring is caused by insufficient ambient light and insufficient light from IR source. The IR source is mounted on the side of the road. Although the source is aimed at the license plate, most of the IR light is reflected away from the camera due to the IR source located

60 degrees to the license plate. Positioning the IR source at a less acute angle would improve light reflection back to the camera.


Figure 138. Not-so typical twilight exposure at the intersection. The exposure was taken in the "sweet spot", where the vehicle is in the proper position to reflect IR back to the camera. The image may also be helped by vehicle headlights pointed east from the west side of US 52 .


Figure 139. Typical nighttime exposure occurring in approximately 75\% of exposures. The variability of the camera shutter release results in a poor license plate angle relative to the camera. Moreover, the vehicle is on the periphery of the IR illumination source, resulting in low light levels reflected back to the camera.


Figure 140. An atypical nighttime exposure at the Minnesota test intersection.
This exposure was taken during (or after) a rainfall. The wet pavement helped reflect IR light from the illuminator, vastly improving lighting conditions. Most of the nighttime exposures captured during wet conditions provided legible license data. Dry asphalt absorbs significant IR energy, lessening available illumination.

