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Final Report

Driver Assistive Systems for Rural Applications: Digital Mapping of Roads for Lane Departure Warnings

Volume 2

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16. Abstract (Limit: 200 words)

Deployment of any system is driven by market demand and system cost. Initial deployment of the Intelligent Vehicle Lab Snowplow Driver Assistive System (DAS) was limited to a 45 mile section of Minnesota Trunk Highway 7 west of I-494 and east of Hutchinson MN. To better gage demand and functionality, St. Louis and Polk Counties in Minnesota operationally tested the system during the winter of 2003-2004; Polk County also tested during the winter of 2004-2005.

Operational benefits were found to be drastically different in the two counties. Low visibility was not an issue with the St. Louis County snowplow routes, so the system offered few benefits. In contrast the topology of Polk county is flat, with almost no trees. High winds combined with few visual cues create significant low visibility conditions. Polk County was pleased with their original system, and obtained a second system and tested it operationally during the 2004-2005 winter. The experience of these two counties is documented in Volume One.

A key component of the DAS is a high accuracy digital map. With the exception of the mapping process, the present cost of the DAS is well documented. This volume, Volume Two, describes a system designed to collect and process geospatial data to be used by driver assistive system, and the costs and time associated with collecting map data, and creating a map from that data. With cost data complete, counties can determine whether to acquire these systems.

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Driver Assistive Systems for Rural Applications: Digital Mapping of Roads for Lane Departure Warnings
Volume 2

Final Report

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Executive Summary

In 2003, 69 percent of vehicle related fatalities in Minnesota occurred in rural areas. Nationally, crashes on rural highways account for 61 percent of traffic fatalities. Rural roads carry approximately 61 percent of the vehicle miles traveled (VMT) each year in Minnesota. Of the traffic fatalities in Minnesota, 52 percent were due to the vehicle failing to remain in its proper lane. Nationally, lane departures are the single most frequent causal factor in fatal crashes. Reducing lane departures has the potential to significantly reduce the number of crashes and fatalities on rural roads.

In order to effectively reduce lane departure crashes, it is necessary to be able to predict when a vehicle may depart its lane. If it is possible to determine the time to a lane departure, then the driver can be alerted. The location, speed, and heading of the vehicle and its relative location to the lane are required to predict when a vehicle will most likely depart the lane. Information about the vehicle's position can be obtained using an onboard high accuracy Differential Global Positioning System (DGPS). Lane boundary information of sufficient accuracy can be stored in a digital map with sufficient detail and accuracy. A DGPS and a digital map together can be used to determine the vehicle's relative position to the lane boundaries within centimeters and can facilitate predictions as to when a lane departure may occur.

Having the accurate location of a lane in an onboard digital map can also aid snowplow drivers in clearing roads in low visibility or whiteout conditions. By combining high accuracy digital maps with high accuracy, dual frequency, carrier phase DGPS, radar, and a conformal, augmented graphical display, a virtual view of the road and obstacles ahead can be provided to a driver when atmospheric conditions would otherwise preclude driving. The graphical display is augmented with an active, tactile seat which complements the visual system by providing vibrational cues to the driver through the seat of where each lane exists, even if the driver cannot physically see the road due to low visibility or whiteout conditions. (The system vibrates the right side of the seat if the vehicle is departing to the right, and the left side of the seat if departing to the left.)

The focus of this document is the creation of a detailed and accurate digital map. In order to create an accurate digital map, the location of the road and its lanes must be determined. This can be accomplished by collecting data for the center of each lane or the physical boundary of the lane. A lane-striping vehicle can collect the lane boundary information during re-striping, or alternatively a computer vision system can be used to locate the lane boundary in an image. These data collection methods can be combined with DGPS to develop an accurate map. Since these methods require a vehicle to travel each road, data collection can be a time consuming process. To create a national database, a quick and efficient method to collect and process map data needs to be developed. Once the road boundary data has been collected, it must be compressed to a manageable size and the digital map must be generated from the data in such a way that other systems can access it without difficulty.

For this document, data collection was facilitated through the use of a computer vision-based system with a camera aligned coaxially with a DGPS antenna. The computer vision-based system locates the lane boundary in the image and uses DGPS, whose dynamic accuracy was previously determined to be 5-8 cm (2.0-3.1 inches) at $\pm$ 1σ, to accurately locate the lane boundary with respect to a global coordinate system. By processing the collected computer vision data and DGPS data in real-time as the vehicle drives along the road, accurate location data of the road can be post-processed into a high accuracy digital map.

The accuracy of the computer vision based system was tested and validated using two separate routes with different geometries: Minnesota State Highway 252 and McLeod County 2. The computer vision-based data for each route was compared against a set of lane boundary fiduciary points. By positioning a DGPS antenna at strategic locations over the lane markings and collecting static data, an accurate set of fiduciary points defining the lane boundaries became available. The accuracy of this method is equivalent to the static accuracy of the DGPS unit, approximately 2-5 cm (0.8-2.0 inches) at $\pm$ 1σ.

All of the raw vision-based data was filtered and compressed using a least squares linear regression fit. In order to maintain accuracy and reduce the data density to an acceptable value, the data points were fit to a series of line segments to within a specified tolerance level. Three tolerance levels, 5, 10, and 20 cm (2.0, 3.9, and 7.9 inches) were chosen to determine the accuracy versus data density trade-off. By using a tolerance level of 10 cm (3.9 inches) or less, it is possible to reduce the data to 1/40th of its original size and achieve a geospatial database that is accurate to within 20 cm (7.9 inches).

With the exception of the DGPS unit, all hardware used to collect and process data was inexpensive and readily available. The total one time cost of the equipment, including DGPS, camera, laptop computer, and the required hardware for mounting the equipment was calculated to be approximately $20,537.00. Since the described system can be retrofitted to an existing vehicle, the cost of purchasing a data collection vehicle is not factored into the cost of the system because interested parties should have a vehicle that can be used for data collection. However, the portion of the salary of a data collection vehicle operator, who collects data 30 weeks out of the year, was determined to be $31,000.00 per annum (benefits included) and vehicle gas and maintenance was determined to be $19,152 per year.

Verification of the data is performed using a Vision Enhancement System (VES), which includes a Head-Up Display (HUD). This additional equipment, which can be installed in the same data collection vehicle, represents a one time cost of approximately $7,000. The quality assurance operator, who also works 30 weeks a year, is assumed to receive a $37,000 salary and benefits package over that 30 week period. Since data verification is required for each route, the vehicle cost (gas and maintenance) is the same as for data collection: $19,152 per annum. This results in a total cost of annual expenses for mapping to be $133,841.00 (assuming equipment costs are spent in the first year; subsequent annual costs will be less).

Based on a reasonable daily data acquisition of 231.7 km (144 miles) of road for three days per week and thirty weeks per year, it is possible to digitize 20,857.1 km (12,960 miles) per year. This results in a digital map costing $10.33 per mile of road with an accuracy of 20 cm (7.9 inches). By equipping four vehicles, the entire rural road system for the state of Minnesota could be completed in two years. If 200 vehicles were dedicated to mapping, the entire rural road system in the United States could be accurately mapped within three years at a cost of approximately $61 million.

Definitions and Acronyms

Rural – Area with a population containing less than 5,000 people
IV Lab – Intelligent Vehicles Laboratory – University of Minnesota Twin Cities campus
DOT – Department of Transportation
Mn/DOT – Minnesota Department of Transportation
NHTSA – National Highway Traffic Safety Administration
FHWA – Federal Highway Administration
DAS – Driver Assistive System
GPS –Global Positioning System
DGPS – Differential GPS, centimeter-level accuracy
RTK – Real-Time Kinematic
VRS – Virtual Reference Station, provides differential correction to DGPS
RTF – Radar Target Filter
VES – Vision Enhancement System – uses a Head-Up Display (HUD)
GIS – Geographic Information Systems
GSD – Geospatial Database
GUI – Graphical User Interface
Fog Line – Outermost lane marking separates driving lanes from shoulder or barrier
HA-NDGPS – High Accuracy-Nationwide DGPS – FHWA
IMU – Inertial Measurement Unit, consists of rate gyros and accelerometers
LiDAR – Light Detection and Range
RND – Road Network Databases
NSSDA - National Standard for Spatial Data Accuracy
FCC – Federal Communications Commission
CDPD - Cellular Digital Packet Data

Chapter 1
Introduction

Due to the large number of road fatalities that occur every year, the Minnesota Department of Transportation (Mn/DOT) joined the Minnesota Department of Public Safety, the University of Minnesota's Center for Transportation Studies, and the Minnesota State Patrol to create a program called "Toward Zero Deaths" (http://www.tzd.state.mn.us/index.html) that attempts to reduce the 600+ annual traffic fatalities and life-changing crashes in Minnesota. Every year 69 percent (Table 1.1) of the total vehicle related fatalities in Minnesota and 61 percent nationally occur in rural areas [1] (rural areas are defined as containing a population of less than 5,000 persons). Clearly, reducing fatalities in rural areas should be a national priority.

Table 1.1 – 2003 Crashes by population of area (from 2003 Minnesota Crash Facts, Table 1.24)

Population of City or Township	**Fatal Crashe**	**Persons**
100,000 & Over	34	37
50,000 - 99,999	31	31
25,000 - 49,999	37	44
10,000 - 24,999	53	63
5,000 - 9,999	27	28
2,500 - 4,999	12	13
1,000 - 2,499	17	17
Under 1,000	372	422
Total	**583**	**655**

Of the traffic fatalities in Minnesota, 52 percent can be attributed to lane departures crashes (Table 1.2). Vehicular lane departure is associated with a vehicle departing the lane and colliding with another vehicle or fixed objects on the side of the road. Alerting the driver can prevent many of these rural crashes and consequently reduce the amount of fatalities on rural roads.

For a number of years, the University of Minnesota's Intelligent Vehicles Laboratory (IV Lab) has developed systems that assist the driver in difficult conditions. These Driver Assistive Systems (DAS), explained in Section 1.3, help drivers stay in their lane and avoid collisions. These systems use a number of modalities, including visual and haptic feedback, to keep the driver from leaving the lane. To be effective, the system must determine where the lane boundaries are with respect to the vehicle. This requires both a method to sense the location of the vehicle within the lane and a representation of the roadway with which to compare the position of the vehicle. One approach that presently can be used to accurately determine the location of the vehicle is the Differential Global Positioning System (DGPS). GPS calculates an accurate position to within 10 meters (32.8 feet) as a single point on the earth. By using a dual-frequency, carrier phase, differential GPS, the accuracy improves to within centimeters. This will be explained further in Chapter 2.

Table 1.2 – Crashes by diagram (from 2003 Minnesota Crash Facts, Table 1.23)

Diagram	Fatal Crashes	Persons Killed
Rear End	28	30
Sideswipe Passing	12	13
Left Turn -- Oncoming Traffic	15	15
Ran Off Road - Left	99	106
Right Angle	113	135
Right Turn -- Cross Street Traffic	1	1
Ran Off Road - Right	101	106
Head On	99	128
Sideswipe Opposing	4	4
Not Applicable	31	33
Other / Unknown / Incomplete	80	84
Total	**583**	**655**

The location of the road and its lanes, with respect to a global coordinate frame, must be collected and processed into a usable map. Therefore, the focus of this document is the efficient creation of a detailed and accurate digital map.

1.1 Background

Accuracy is the most important measure when creating digital maps used for vehicle guidance and lane departure systems. Traditionally, photogrammetry has been the method of choice for mapping roads when accuracy is a priority. Photogrammetry uses an aircraft equipped with DGPS, high accuracy inertial measurements, and high resolution cameras to capture images of roads or regions of interest. Currently, photogrammetry can produce a map with an accuracy of 30.5 cm (12 inches) or better. A downside to photogrammetry is that it is a very time consuming process, which is skilled labor intensive, and therefore expensive. There are multiple steps involving aerial data collection, creating image mosaics and orthoimages, which may also include manual intervention [2]. Photogrammetry is not performed solely for road location. It is used to create multiple maps concentrating on different characteristics of a single area including the positions of building, waterways, and land topography. Unless the data is readily available, photogrammetry is not a reasonable approach for acquiring digital maps used for lane departure warnings since its accuracy is generally insufficient and the cost can be expensive, $18,000 – $35,000 per mile, depending on the features required.

Photogrammetry is not the only airborne method used for collecting road data. Some companies are using Light Detection And Range (LiDAR) to collect data. Aerial mapping, using LiDAR combined with GPS and an Inertial Navigation System (INS), can give results similar to photogrammetry with accuracy of approximately 30.5-45.7 cm (12-18 inches), depending on aircraft altitude. One company using airborne LiDAR is Optech (http://www.optech.ca/).

LiDAR can collect the same features (buildings, roads, waterways, topography, etc.) as photogrammetry, but yields a faster turnaround time. McNabb [3] has created a 90,000-km^2 map of buildings, roads, waterways, and topography with an accuracy of 50.8 cm (20 inches) in 15.5 hours.

Satellite imagery is another method of acquiring data. The resolution of satellite imagery is typically on the order of one image pixel equivalent to 10 by 10 meters (32.8 by 32.8 feet) [4]. This method is useful for topographic map creation where features can be located. SPOT-5, a satellite component of the SPOT program developed by France, Belgium, and Sweden, increases the resolution to 2.5 meters (8.2 feet). However, a major issue is the accurate differentiation of the features in the image. By using software for detecting roads in satellite imagery, many roads can be extracted automatically. However, the satellite imagery resolution is not sufficient for detecting individual lanes on a road, just the location of the road.

For many applications, ground-based road data collection is a cheaper and easier method than aerial road data collection. By using GPS and INS, one can achieve high accuracy maps on the order of 1-3 meters (3.3-9.8 feet). This method has been employed by a number of groups wishing to generate inexpensive, high accuracy maps. In this situation, the data acquisition system is mounted onto a vehicle, which drives the road network and creates the map. Wilson and Rogers [5][6] use multiple vehicles equipped with GPS units to create and refine maps. It is possible to construct these maps using the data collected from drivers going about their everyday activities. By initializing their system with a commercial map accurate to 7 meters (23.0 feet) as a baseline, Wilson and Rogers improved their accuracy to 1-2 meters (3.3-6.6 feet).

The National Highway Traffic Safety Administration (NHTSA) and the Federal Highway Administration (FHWA) funded a consortium of automakers called the Crash Avoidance Metrics Partnership (CAMP) to create highly accurate digital map databases and related active safety systems as part of the Enhanced Digital Map (EDMap) Project [7]. The EDMap project team consisted of DaimlerChrysler, Ford, General Motors, and Toyota along with a commercial map company, Navigation Technologies (NavTeq) (http://www.navteq.com). They worked to develop a number of enhancements to digital maps that would improve the performance of driver assistance systems. The EDMap Project's map includes the road geometry, the width of each lane, as well as the GPS locations of signs and traffic signals. In November of 2004, EDMap released their final report detailing their progress. Focusing on their geometry accuracy, they stated that their "near-term map databases" have 72% of their data within 1 meter (3.3 feet) and 85% within 2 meters (6.6 feet). Their "mid-term map databases" have 51% of the geometrical data within 30 cm (11.8 inches) and 96% within 2 meters (6.6 feet).

A second project creating large-scale accurate digital maps is being carried out in Finland. They are working on creating a high accuracy road network for the entire country. This project, titled DIGIROAD [8], integrates the data from the Finnish Road Administration (Finnra), the National Land Survey of Finland, Finnish city road databases, and the forestry industry to create maps with an accuracy of 1-3 meters (3.3-9.8 feet). Not only is the centerline geometry being collected, but other attributes that define the road network are also being stored. The database will also include other features that may be important such as freight terminals and public transport facilities. Since the entire country is scheduled for mapping, they will not integrate any real time data; map updates may take up to three months before they are included. Initially, Finnra will allow access to DIGIROAD free for public use, but will charge private companies an annual fee.

NextMAP, which concluded in 2001, was a project funded by the European Commission's 5th Framework Information Society Technologies Program and managed by the European Road Transport Telematics Implementation Coordination Organization (ERTICO). It was a consortium of five car manufacturers (BMW, Centro Ricerche Fiat, DaimlerChrysler, Jaguar, and Renault) and two map providers (NavTeq and TeleAtlas). Their goal was to assess and evaluate the feasibility of digital map databases for Advanced Driver Assistance Systems (ADAS). The map providers created their maps primarily using aerial imagery to an accuracy of 4 meters (13.1 feet) [9][10].

Ohio State University's Center for Mapping (CFM) used GPS/INS and cameras to locate the road boundaries. They were interested in locating the edges and centerlines on a road while traveling at highway speeds. In order to do this, they instrumented a vehicle, the GPSVan^{TM}, dedicated to collecting data [11]. By mounting a digital camera on top of the GPSVan^{TM} at a five-degree downward angle one meter from the GPS antenna, they could collect the road boundaries while driving. Data was collected at 15 Hz, which resulted in a 60-percent overlap in each image. It was then stored for later use and processed using a line-following algorithm. This resulted in a map that was accurate to approximately 10 cm (3.9 inches). The GPSVan^{TM} project is no longer an ongoing project at the CFM.

Applanix Corporation (http://www.applanix.com), a subsidiary of Trimble Navigation Ltd. (http://www.trimble.com), has a mobile mapping system combining GPS, an inertial measurement unit (IMU), a distance measurement indicator (DMI), and a computer system. This system, Position and Orientation System for Land Management (POS LV), uses Inertially-Aided Real-Time Kinematic (IARTK) technology which provides continuous position and attitude data, even under situations that are difficult for a stand alone GPS system to achieve accurate position and orientation information such as within urban canyons and along tree lined roads. The POS LV system automatically integrates raw GPS satellite data into the system thereby allowing the system to use position data from a single GPS satellite observable. Since the POS LV system does not use the position and velocity information from the GPS receiver, it works very well in a urban situation and can maintain a decimeter-level positional accuracy horizontally and a meter-level accuracy vertically [12].

1.2 University of Minnesota's Geospatial Database

The University of Minnesota's IV Lab previously developed a Geospatial Database (GSD). Newstrom [13] created the GSD, which facilitates many driver assistive systems including lane departure warnings. The GSD contains digital representations of spatial objects that represent the geometry of the real world landscape.

The geometry of the roadway, as well as road furniture, is represented in order to give a detailed description of the roadway. Road furniture includes man-made physical features in or around the road such as signs, lampposts, and Jersey barriers. Newstrom [13] created a custom geospatial database rather than manipulating commercially available digital maps.

Current commercially available digital maps are based on digital road network databases (RND) that are primarily used for route determination, point-by-point driving, and Geographic Information Systems (GIS). Road network databases are composed of links and nodes that model the roadway and use or are based on linear-reference systems. Linear reference systems reference data to the nearest node and the distance along the connecting link. Since many intelligent transportation systems rely on GPS for the position of the vehicle, converting between the linear reference system and a Cartesian coordinate system would add unneeded complexity to the DAS.

Navigation Technologies, Inc. (NavTeq) and TeleAtlas (http://www.teleatlas.com) are two commercial companies that have created digital maps based on RNDs. Their map databases provide their customers with turn-by-turn or door-to-door navigation, also known as route guidance. NavTeq provides their maps to Mapquest (http://www.mapquest.com) and automotive manufacturers including General Motors for use in their in-car navigation systems. These systems are designed to augment onboard navigation systems and provide directions. However, their architecture, accuracy, and resolution are not sufficient for applications in which lane departure warning is necessary.

Instead of using RND-based digital maps, Newstrom [13] created a geospatial database that uses spatial objects defined relative to a global coordinate system. These geospatial databases (GSD) use points, line-strings, arc segments, and polygons to define the scene rather than the links and nodes used by RNDs. Points are defined as single three-dimensional objects and a line-string is a continuous series of points. An arc segment is a series of points that are a part of a circle and contain the center point of that circle. Polygons are a special type of line-string; they are closed, sharing start and end points.

Whereas the points, line-strings, arc segments, and polygons can describe the spatial object, something must define other non-spatial objects that aid in the definition of the data set. These non-spatial identifiers or attributes are static and assigned during the creation of the geospatial database. Different attributes are assigned based on what the road data represents.

There are four types of road data models described in [13] with an additional four created later [14]. These define the road and the surroundings. The original four are listed as lane boundary (line-string), road shoulder (line-string), centerline (line-string, arc-segment), and road-island (polygon); the added four are Jersey barrier (line-string), guardrail (line-string), sign (point), and mailbox (point). The first three, lane boundary, road shoulder, and centerline, describe the actual road. Lane boundaries are the leftmost and rightmost limits in each lane, typically shown as painted lane markings. The road shoulder edge defines the boundary of the drivable surface [13]. This can be a painted lane marking, the edge of the physical pavement, or a physical object barring departure from the road. The centerline is midpoint between the lane boundaries and one exists for each unique lane. The remaining data types, road island, Jersey barrier, guardrail, sign, and mailbox, are all types of road furniture that are near the road.

1.3 Geospatial Database Applications

The IV Lab has developed four onboard driver assistive systems (DAS) that require the use of the geospatial database. These systems can be used separately or in conjunction with each other. The four DAS systems are the Vision Enhancement System (VES), the virtual mirror, the radar target filter (RTF), and the haptic feedback systems. Each of these systems relies on the accuracy of the geospatial database in order to effectively function.

By knowing the location of the vehicle through high accuracy DGPS and by using an accurate GSD, it is possible to project a high fidelity view of what lies ahead of the vehicle. Through the use of a Head-Up Display (HUD), the VES projects an image of the lane boundaries and other items that overlay the real lane boundaries. The HUD uses the geometry found in the geospatial database to construct an image of the lane boundaries and road furniture along the roadway as it appears from the perspective of the driver. The driver views this image through the use of a combiner, a spherical semi-reflective, semi-transmissive section of optically treated glass or optical grade plastic that is located between the driver and the windshield. The driver looks through the combiner and can see the virtual road projected directly over the actual road, as shown in Figure 1.1. This is useful if the actual view of the road becomes obstructed or the visibility is reduced [15][16][17].

Figure 1.1 – View through the HUD

The virtual mirror utilizes an LCD computer screen and creates a digital representation of vehicles around the vehicle. It displays the lane boundaries and any road furniture adjacent to vehicle. It serves as an adjunct to the physical, optical mirror in a vehicle and draws the obstacles and the geometry next to, as well as behind, the vehicle. By using a mirror-like representation, the system takes advantage of the driver's intuitive ability to respond to objects viewed in the mirror. An advantage of this system is that it is not constrained by physical properties and can eliminate or at least decrease the blind zone around a vehicle. This is particularly an issue for buses and trucks.

The radar target filter (RTF) uses a number of radar units that detect objects around the vehicle. Since radar is indiscriminate, any object in the radar's field of view, such as a vehicle, sign, or tree, is a valid target. In order to determine if the object is a threat, the radar target filter uses the geospatial database's road geometry to determine if the object is on or off the road. Road furniture, which are adjacent to the road, are static objects that define the road or inform a driver about the road, but are not considered a threat. If an object is not on the road, the radar target filter filters it out. Any valid objects are then displayed in the VES or virtual mirror as obstacles.

The haptic feedback system provides continuous feedback to the driver about the offset of the vehicle from the centerline. This is accomplished using two different subsystems, feedback through the steering wheel and feedback through the driver's seat. As the vehicle approaches the lane boundary, a servomotor excites the steering wheel. This excitation can either simulate the vehicle traveling over a rumble strip or produce a torque proportional to the lateral offset of the vehicle from the lane center. In the latter case, the haptic feedback system can indicate to the driver which direction they should steer so they remain in their lane. The driver's seat uses a number of embedded motors that produce localized seat vibrations. As the vehicle moves away from the center of the lane (left or right) and close to the lane boundary, the corresponding side of the seat vibrates alerting the driver to a potential lane departure on that side.

Accuracy is of the utmost importance with all four systems and any mismatch in geometry can lead to serious consequences. While using the VES, an inaccurate geospatial database may lead to fatigue and/or distraction even in clear driving conditions. If the geospatial database is not aligned with the physical road, the virtual mirror and radar target filter may not be able to distinguish what is on and off the road. If the road geometry does not accurately match the real world geometry, the haptic feedback system may unintentionally force a lane departure.

1.4 Report Layout

Thus far, the need for and the concept of a geospatial database has been discussed. The remainder of this document details the implementation of a data collection system to create geospatial databases efficiently and the experiments that have been conducted to analyze the accuracy of the data collection system.

Chapter 2 defines a road model based on road design standards and assumptions that enable efficient data collection. In order to collect the road information as accurately as possible, DGPS will be used. The method used to receive a differential correction is also explained.

In order to accurately locate the road, a computer vision system is described in Chapter 3. The computer and camera requirements are also explained in order to use the software to collect accurate data in real-time.

Chapter 4 explains the required post-processing work. Although data is collected in real-time, the final geospatial database files can be created offline in the vehicle and with very little intervention.

Data collection using the computer vision system was performed on a state highway and county highway. Chapter 5 describes the accuracy results of the system as compared to ground truth.

Costs for equipment and personnel are described in Chapter 6 in order to determine the feasibility and price per mile the map data acquisition system requires.

Chapter 2
Data Acquisition

This chapter describes a method to acquire the accurate location of a road. In order to do this effectively, the road must be defined in a way that will facilitate data collection in an efficient manner. Once the road is defined, its position must be accurately located.

2.1 Road Definition

Through the use of road design standards it is possible to make a number of assumptions that hold true under most circumstances when modeling the actual road. The assumptions made here affect the method of collecting the raw data and processing it into a useable map.

It is possible to assume that the roads contain markings that identify and separate each individual lane. This is more a fact than an assumption. However, this may not be the case with residential roads. Since very few fatal crashes occur on these roads, they will not be the focus of this effort. Moreover, for snow removal operations, low visibility is rarely an issue in residential neighborhoods.

Adjacent road lanes are effectively parallel to each other. In cases where the road is divided by some physical object (median, Jersey barrier, guard rail, etc.) all lanes traveling in the same direction are parallel to one another. For roads that are undivided, all of the lanes, regardless of direction are parallel. Even in the case where a lane addition or reduction (adding or removing a lane along the road) takes place, these lanes are parallel but their respective lane boundaries may not be. Since most lane additions or reductions occur to the outside lanes, the right or leftmost lane boundary, herein defined as the fog line, may cease to be parallel for short distances with respect to the other lane boundaries. This fact does not alter the assumption that the lanes themselves are parallel.

Fog lines define the outermost visible lane marking in the right- or left-most lane. They are not to be confused with the data type *road shoulder*. The road shoulder, mentioned earlier, defines the extent of the drivable surface. In the case where a median, Jersey barrier, or ditch separates the opposing directions of traffic, shown in Figure 2.1, there exists a fog line to the right of the rightmost lane and one to the left of the leftmost lane. This is true regardless of the road direction. In the case where the two directions of traffic are not separated by a physical boundary, Figure 2.2, all that remains is a single fog line in each direction, the rightmost (based on a road system in which vehicles drive on the right). It is then possible to define a road if the fog lines are known.

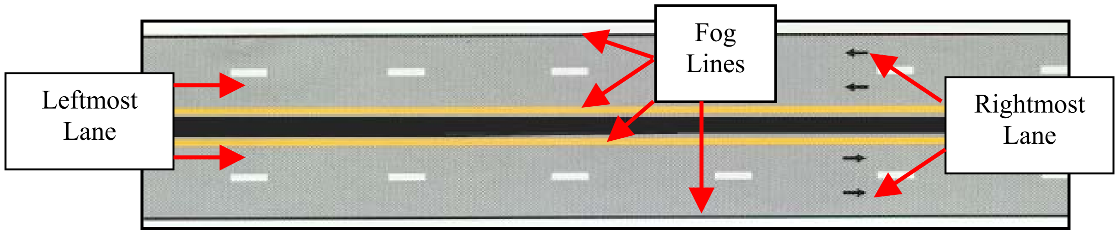


Figure 2.1 – Multi-lane, divided highway

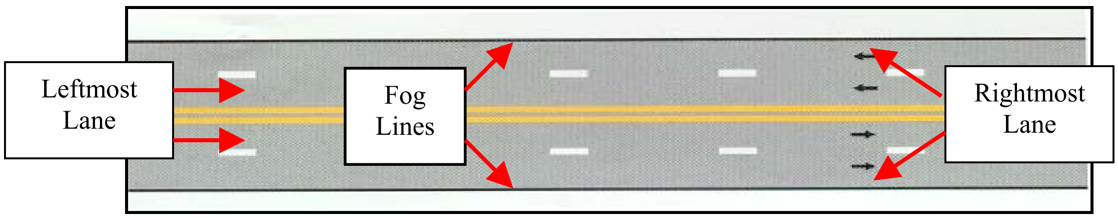


Figure 2.2 – Four-lane, non-divided highway

Knowing that fog lines define the road, a new constraint is introduced. Each road, regardless of the number of lanes or their direction, requires two fog lines.

By focusing on a map needed for prevention of lane departure crashes, it is possible to concentrate on rural roads. Intersection details (i.e. dedicated left-turn and right-turn lanes) can be ignored because they are not significant in lane departure crashes. These can be dealt with using other methods when needed for other applications. In this document, the focus will be on the details of a geospatial database that is needed for lane or road departure warning on rural roads. However, the result of this research (i.e. the map) can also be used for road maintenance purposes, such as snow removal operations, when visibility is poor.

Therefore, this document will discuss mapping in the context of parallel road fog lines and lane boundaries. Other road features not relevant to lane or road departure will be ignored.

2.2 Data Collection

The procedure for collecting data can be discussed in the context of the stated road definition. As mentioned earlier, the fog lines define the edges of the physical lanes in each direction. If these are accurately defined, it is then possible to define the entire road. The width of the lanes may introduce a problem. In Minnesota, most interstate, state, and county highways use 3.7 meter (12 feet) - wide lanes. However, in many places on state and county roads, lanes can be reduced to 3.0 meters (10 feet) wide. However, if the number of lanes is known, in addition to the placement of the fog lines, then the road can be defined regardless of the lane width.

There are three separate cases that need to be considered. The first, shown in Figure 2.3, is the case when a double yellow line divides the opposing lanes of traffic. Figure 2.4 shows a second situation where a physical barrier divides the directions. This physical barrier can be a guardrail, Jersey barrier, or a median of some type. Finally, there is the case when there is a special lane that exists, as shown in Figure 2.5. This special condition occurs when there is a two-way left turn lane in the center of the road, also known as a “suicide” lane. The lane in between the lanes of traffic exists solely for left turns. On a two-lane, non-divided highway, vehicles that wish to turn off of the main artery and onto a minor road can obstruct traffic and cause rear end crashes. With the addition of these left-turn-lane-in-center lanes, vehicles can leave the main traffic flow and not obstruct traffic while waiting to turn left.

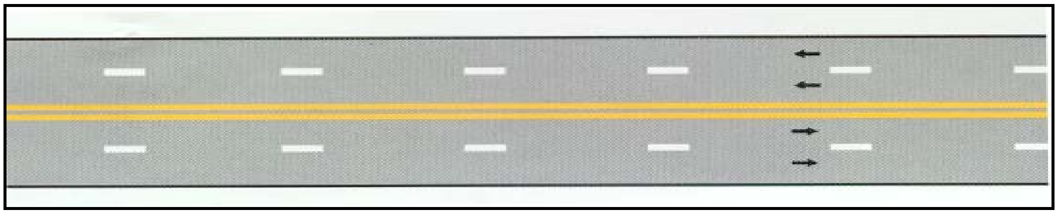


Figure 2.3 – Four -lane highway, double yellow divider

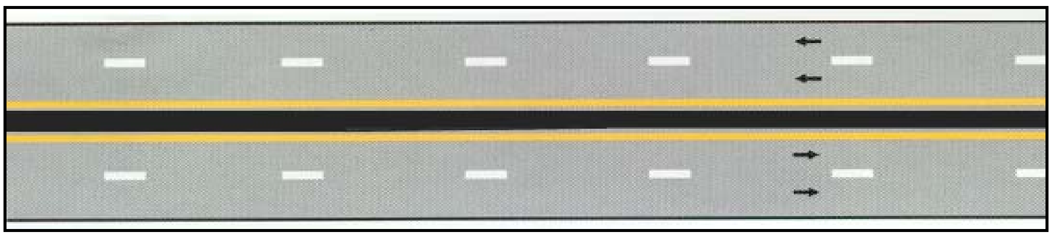


Figure 2.4 – Multi-lane, divided highway (Jersey Barrier)

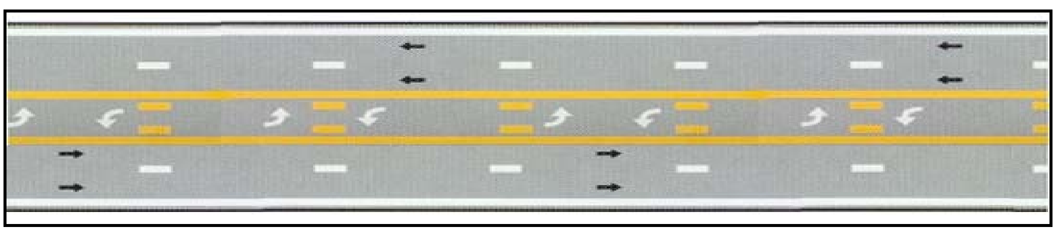


Figure 2.5 - 4-Lane highway with left turn lane in center

In Figure 2.3, there exist two fog lines. Each fog line lies on the right side of the respective directions on the road. The data collection vehicle needs only to drive each direction once with data collection taking place on the right side of the vehicle if the lane widths are known. While the pictured images have two lanes per direction, the data collection vehicle will only need to drive each direction once regardless of the number of lanes between the fog lines.

In Figure 2.4, there are two lanes in each direction, and four distinct fog lines. Each direction of travel contains two fog lines, one on each side. In this case, data must be collected for each fog line and the vehicle must make two passes in each direction, collecting data on the right side for the right fog line and on the left side for the left fog line.

Figure 2.5 shows a situation where there is a left turn lane in the center of the road. Typically this is only one additional lane. However, because its width is unknown, it will be treated in a similar manner as a divided highway as shown in Figure 2.4.

2.3 Global Positioning System

The Global Positioning System (GPS) [18] consists of 24 satellites in 6 orbital planes with each satellite circling the earth in 11 hours and 58 minutes. At any given moment on the earth's surface, there are between 6 and 12 satellites available above the horizon. These satellites broadcast data including an accurate timestamp of when the data left the satellite. Stations on the ground can receive this information and calculate the distance to the satellite. Knowing the distance to multiple satellites allows the receiver to triangulate its position to within several meters. This is known as a single point fix. Due to timing errors and propagation delays in the ionosphere, the unaugmented single point position is accurate to 10 meters (32.8 feet).

2.3.1 Differential GPS

Ten meters is far from accurate enough for any diver assistive system. In order to increase the accuracy, Differential GPS (DGPS) is used. DGPS requires a GPS receiver and an additional antenna located on the ground at a known, surveyed location (a base station). The base station compares its location against the calculated position from the satellites and computes a representation of the error. This position error is known as a *differential correction* and it is transmitted to a receiver (roving receiver) requesting an accurate position. The IV Lab uses a Trimble MS750 DGPS unit, which is a dual-frequency, carrier phase, Real-Time Kinematic (RTK) unit, because high positional accuracy is required. The static accuracy of this system is on the order of 2-5 cm (0.8-2.0 inches) at $\pm 1\sigma$ and has a dynamic accuracy of 5-8 cm (2.0-3.1 inches) at $\pm 1\sigma$.

2.3.2 Real Time Provision of the Differential Correction

Once the difference between the surveyed location of the base station and the calculated position determined from the GPS satellites is known, this information is broadcast to the roving receiver. This can be done in several ways. The IV Lab has extensively used two different methods. The first method is through the use of a radio frequency modem. This requires a radio modem, an antenna, and an FCC license. DGPS is based on common mode errors. However, beyond a certain distance, common mode assumptions fail and a reliable correction is difficult.

A second method used by the IV Lab for receiving the correction is through the use of digital data channels on cellular phones. This method is very similar to that of the radio modem, but it does not require an additional FCC license. The cell phone provider handles the license and a correction can be received as long as the cell phone is within the cell phone provider area. The IV Lab used this method almost exclusively with a Virtual Reference Station correction explained in section 2.3.3.

2.3.3 Virtual Reference Station

There is another way to receive a differential correction without the need of a dedicated local base station. Network solutions for differential corrections utilize multiple base stations that have been accurately surveyed. While this is similar to a local base station, these stations send the raw satellite observables to a central server. Raw observables are used to compute a least squares optimal solution for any coarse position located within the area between the immediate outermost base stations. Users of this correction method can access the servers via wireless connection. The wireless connection can be in the form of a Cellular Digital Packet Data (CDPD) modem, a line relay server, radio modems, or the use of a cellular phone capable of high-speed data transfers. The user's uncorrected GPS point is sent to the server and is used as a seed value from which a correction is determined and then transmitted back to the user.

Mn/DOT currently operates such a system, Trimble's (http://www.trimble.com) Virtual Reference Station (VRS), along Interstate 94 from Wisconsin to North Dakota. As shown in Figure 2.6, they operate 32 stations located at the intersections of the lines. By July 2005, Mn/DOT hopes to expand the coverage of VRS by 17 stations that would cover most of Minnesota. The proposed coverage is pictured in Figure 2.7. Data is typically sent using high speed, data capable cellular phones. Unfortunately there is not a single wireless carrier that has the ability to supply a digital signal, which is required for digital data transfers, for the entire state of Minnesota. In some cases, short-range (3.2-4.8 km, 2-3 mile) radio broadcasting can augment the correction.

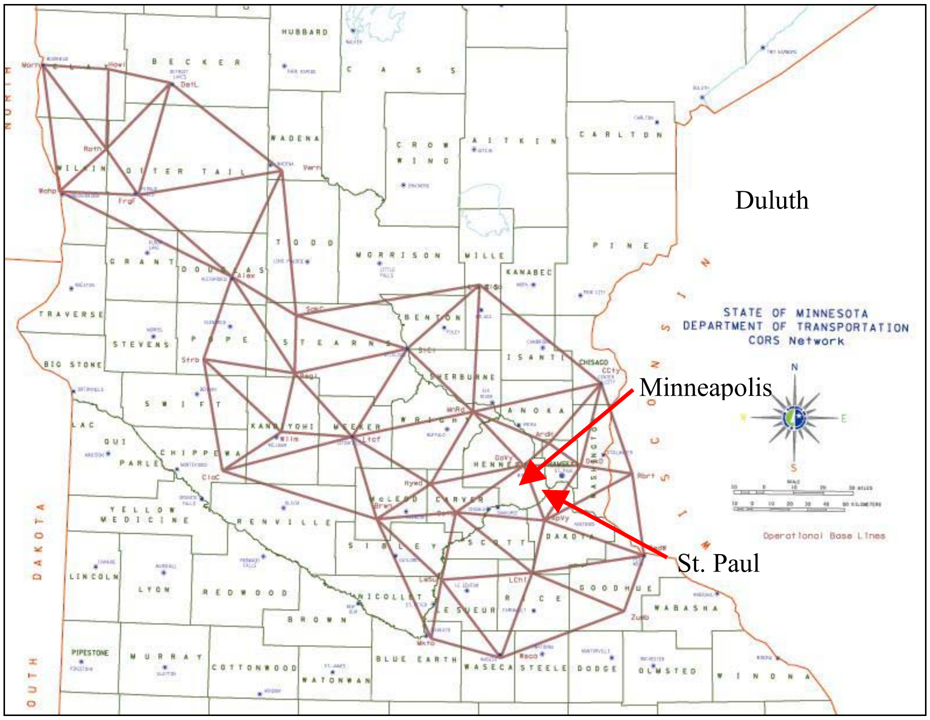


Figure 2.6 – Current Mn/DOT VRS coverage

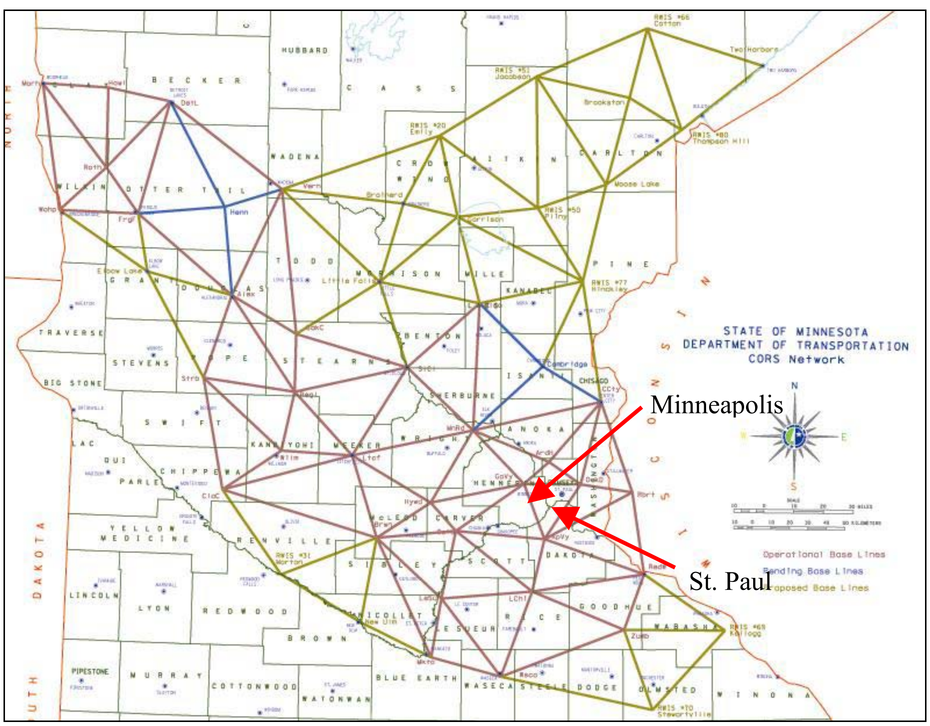


Figure 2.7 – Proposed Mn/DOT VRS coverage by July 2005 (Source: Mn/DOT Office of Land Management)

Chapter 3
Vision-based Data Collection

In all of the vehicle-based data collection techniques mentioned in Chapter 1, the accuracy of the data with respect to a world coordinate frame is critical. It is next to impossible for any vehicle operated manually to remain perfectly centered in a driving lane. It has been shown in [19][20] that drivers can deviate laterally as much as 25.4 cm (10) inches within their lane while driving under normal conditions. Collecting data in a single pass is normally not accurate enough for creating a map used for a lane assistive system for the prevention of lane departures. It also produces a less than favorable view in a HUD based vision enhancement system. If the data collection process exhibits this much inaccuracy, then the resulting map will have inaccurate centerlines, lane boundaries, and road shoulder demarcations.

Data collection can be improved using other methods. The simplest approach, although time-consuming, is to average multiple runs. The data collection vehicle is driven along the same lane multiple times and the data is averaged together. This method results in a map that has a good accuracy but can be biased due to the driver's preference. If a driver is consistently biased towards the left lane boundary during the drive, the data for the lane will consequently be biased to the left and vice versa. While shifting the data can negate this, it can be a time consuming manual modification. Another downside to this method is the number of runs required for each road. If the area requested is very large, it can be very time consuming to collect the data. A similar method was used by [5][6] where multiple drivers are employed to collect the data instead of a single driver. Using multiple drivers instead of one can effectively remove the bias, but it fails to reduce the time required for data collection.

A different and more accurate method would be to employ a lane-striping machine. As mentioned in Chapter 2, the fog lines, which are lane boundary markings, define the road. The use of the line-striper as a data collection vehicle is advantageous since it creates the physical lane marking that defines the road.

By tracking the location of all paint nozzles or striping tape-applying mandrels with respect to a high accuracy DGPS system located on the vehicle, one can readily (and for relatively little incremental cost) digitize the roads.

Roads are repainted only when they require it. In Minnesota, interstates typically use tape or epoxy lane markings. Tape can last from 10 to 12 years whereas the epoxy only marking lasts from 2 to 5 years. A third type of lane marking that is applied is latex based. Latex, which has a life span of about one year, is common and is used on state and county highways. Presumably, it would take a number of years to map every road if data collection occurs only when the stripes are repainted. Painting for the sake of data collection could be quite expensive. However, a method based on lane-striping equipment would only require a single pass to generate an accurate collection of data.

The main issue with using a lane-striping vehicle is that the operators are busy with the striping process and the data collection may require a dedicated operator or an autonomous mapping system. Lane-striping equipment is expensive to purchase and may not be available if a DOT contracts a company to repaint lane markings. However, since the lane markings are visible, there exists another method for locating the lane marking: a computer vision-based approach integrated with DGPS.

3.1 A Computer Vision-Based Approach to Data Collection

There are a number of ways using computer vision based methods to locate a simple geometric object in an image. Ohio State University's Center for Mapping [11] (discussed in Chapter 1) used a camera to aid in the determination of the lane marking position. However, this system is not a unique application. Cameras and computers can be used in numerous ways for mapping applications and to locate entities visually. Many times, the camera is used to collect a multitude of objects, not just the road. This is the case in [11][21][22]. In all of these cases, the camera is either forward looking or positioned with a downward angle. This camera orientation provides a larger perspective view of the scene.

This chapter will describe and explain an integrated DGPS and vision-based system that is used to quickly and accurately collect lane boundary data. This results in an efficient use of time collecting data for the purposes of creating a high-accuracy geospatial database. Figure 3.1 illustrates the vision-based system flowchart that will be followed in this chapter. In section 3.2, the vision-based data acquisition system will be described and the image processing algorithms will be explained in section 3.3.

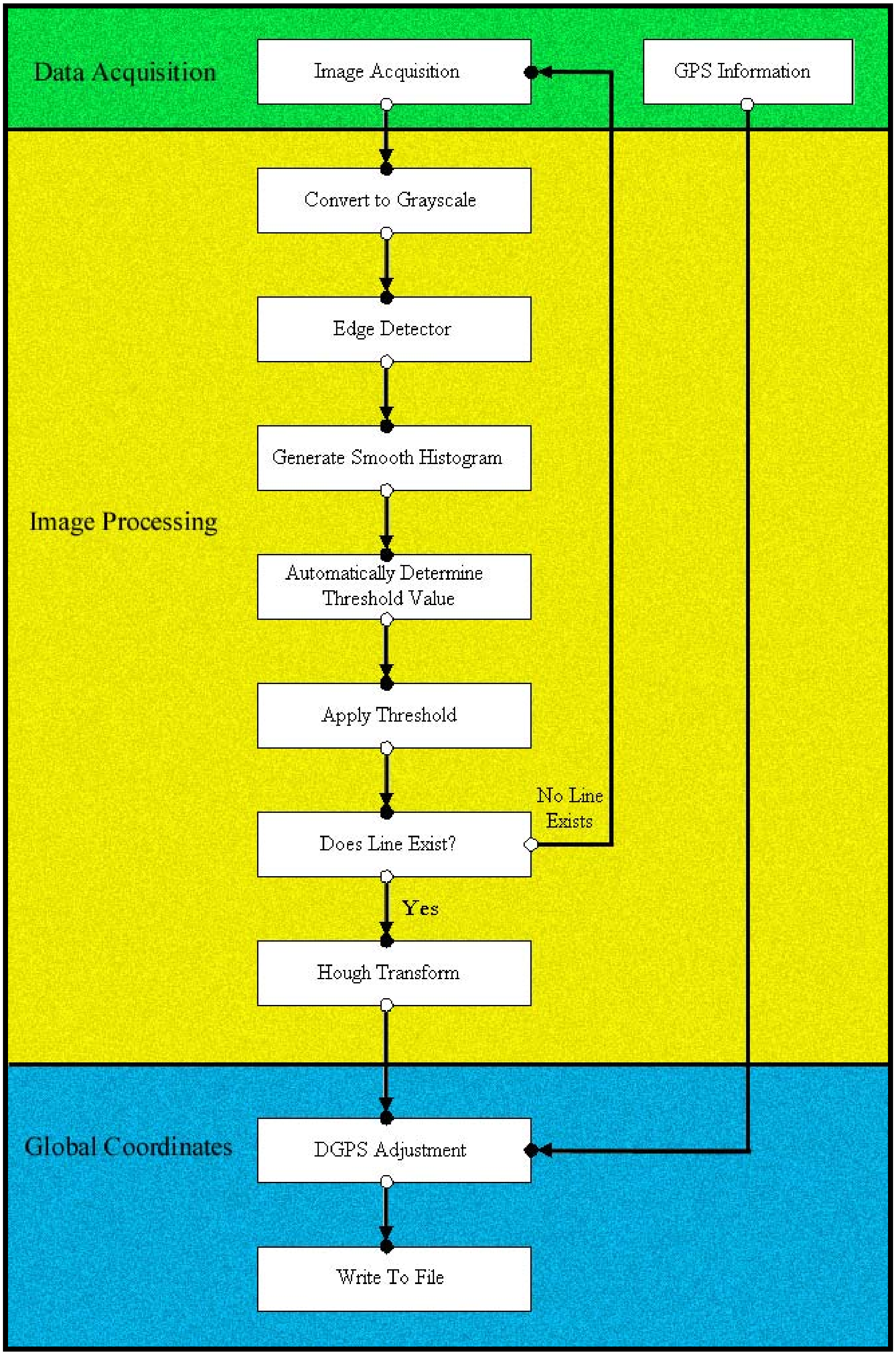


Figure 3.1 – Vision-based system flowchart

3.2 Data Acquisition

The Intelligent Vehicles Laboratory at the University of Minnesota operates an International model 2450 truck, normally used as a snowplow (the SAFEPLOW) as a test bed for many new IV Lab systems. The SAFEPLOW is a useful data collection vehicle since it is equipped with strobe lights that alert people to its location. All experiments to collect data were performed using the SAFEPLOW.

3.2.1 Camera

In order to use a computer vision system, a camera was mounted to the exterior of the SAFEPLOW. Most cameras require an image capture board, which is an additional piece of hardware. However, due to an increase in the use of the Internet, there has been a market niche for cheap cameras that are used to broadcast images over the web. Typically, these cameras connect to a computer using the Universal Serial Bus (USB). Using this interface, there is no need for an image capture board. However, the resolution tends to suffer and the image may not be as crisp as a high-end camera, especially when the scene is in motion.

Since the focus of the data collection is the lane marking, the field of view can be restricted to the lane marking. The resolution is inconsequential due to the proximity of the camera to the actual lane marking and to the fact that it is a simple geometric shape. This allows the exclusion of an image capture board and the ability to use a simple web-based camera with a USB connection.

3.2.2 Illumination

The quality of the image processing will depend on the quality of the image. This can be affected by many things, most of all by illumination. An image can change based on the dynamics of the ambient light. If the illumination of the scene can be controlled, the ambient light is less of a factor. In an outdoor environment, there exist two extremes, day and night. During the day, the illumination is affected by the time of year, the cloud cover, the position of the sun, nearby physical objects (i.e. trees, buildings, etc.), which can temporarily reduce the available light or introduce shadows. Operating at night offers fewer problems than the day. Cloud cover, the cycle of the moon, and the placement of streetlights, can still affect the available light. However, at night there is a better opportunity to control the illumination through the use of an external light source.

3.2.2.1 Light

It is important to illuminate the scene so that other light sources, streetlights, vehicle headlights, etc., do not substantially alter the scene. By using a halogen light to illuminate the area that the camera is capturing, it becomes possible to maintain a uniformly lit scene under a variety of conditions. However, most lights are typically spotlights. A spotlight will have a bright center "spot" with reduced intensity in concentric rings moving away from the center. If the software is too sensitive to minor intensity changes, a spotlight can produce false edges. Painted lane markings may cause problems because they are retro reflective. Retro reflective material is engineered to reflect the light along the same path it was received. If the light "spot" is trained on the lane marking, the light is reflected back and the lane marking can disappear in an area known as a "wash out." This happens when the camera receives too much light and the area appears as a large white spot. This is an undesired result and can be dealt with by correctly positioning the light and using a diffuser.

A diffuser is a piece of optical glass that alters the angular divergence of the light. An opal glass diffuser thoroughly diffuses the light and produces a near Lambertian source. By placing the diffuser in between the light source and the scene, a uniform intensity is produced. This reduces or removes the effect of a spotlight and subsequent "wash out" when the lane marking and light center coincide.

3.2.3 Computers

The computer that is running the software must be able to collect information from the DGPS receiver, and the camera, and run the required software. The image processing software used for the experiments was written in the C language and designed to be operating system independent. While the software can run on Windows, Linux, Unix, or QNX, Windows 2000 Professional was the operating system used.

3.2.3.1 Computer Processor Speed

Aside from the operating system, the computer's processing speed is a concern. Restricted by the acquisition speed of new DGPS position information at 10 Hz, the software must run in real-time and with a processor speed fast enough for real-time processing of all data. A Pentium III, 1.26 GHz dual processor computer was used for collecting data.

3.2.4 GPS

When the camera acquires an image, a DGPS position is captured at the same time. This DGPS position corresponds to the location of the vehicle when the image was captured and will be used in Section 3.4.

3.3 Image Processing

Attention was focused on an approach in which the field of view is limited and oriented to optimize the accurate tracking and isolation of a lane marking. In this case, the object under investigation is a line that consumes the majority of the image. The background is always either dark (asphalt) or light (concrete) and the line in the image is either white or yellow. Even though the possibility of a white line on a light background exists, the colors are not the same shade and the lane marking can be identified. To further enhance this difference, the camera image was always converted to a gray scale. This conversion can be done in one of two places: either using a gray scale camera or by using the appropriate software with a color camera. Once the image is converted to gray scale, the lane marking can readily be detected.

3.3.1 Gray Scale Image

Each pixel in an image, whether color or gray scale, has a numerical value that reflects its intensity. In a gray scale image (8 bit), the intensity value varies between a black pixel (0) and a white pixel (255). When observing a single lane marking in an image, there are two defining characteristics, as shown in Figure 3.2.

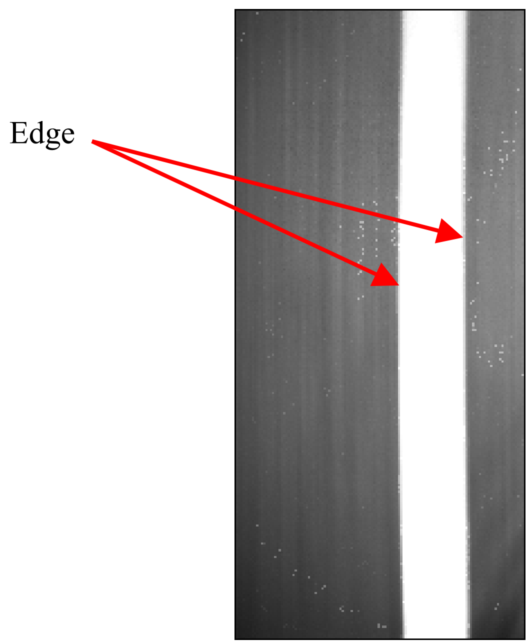


Figure 3.2 – Gray scale image – white lane marking on black background

The first characteristic is the boundary, or edge, between the lane marking and the background. There are two edges in the image shown and they define the width of the lane marking. The second characteristic is the fact that the area between to two edges has a relatively uniform intensity. The background doesn’t have a uniform intensity, but its intensity relative to the lane marking’s intensity, is significant. This allows the use of an edge detector to find the lane marking in the image.

3.3.2 Edge Detector

An edge is located by finding where the gray level intensity rapidly changes. Edges are associated with intensity discontinuity in the image. The discontinuity marks the rapid change from the background to the white lane marking and vice versa. This can be shown as a simple step plot in Figure 3.3. The rapid change occurs when moving from the background pixels (pavement background) to the pixels that capture the lane marking.

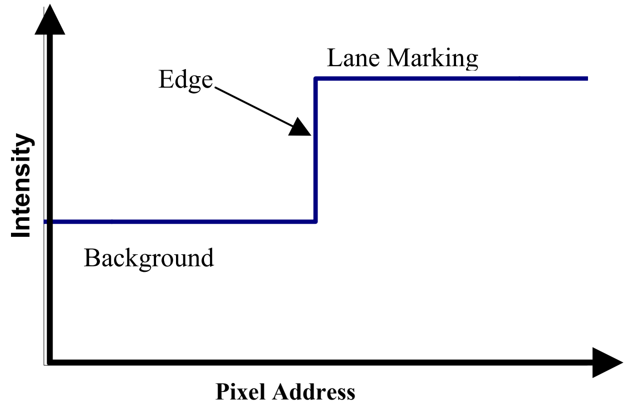


Figure 3.3 – Step edge

An edge detector generally consists of two convolution masks, one for each direction. These masks are specifically designed to enhance the rapid intensity changes.

Each pixel, and its neighboring pixels, is examined to determine if there is a rapid intensity change. In order to determine this, a convolution is used. A convolution blends one function with another one. For edge detection, a convolution mask is blended with the image. The mask uses the neighboring pixel values and a weighted value to enhance the edge. The number of neighbors that are used dictate the size of the convolution mask. The larger the mask, the more sensitive it will be to locating intensity changes. The mathematics required for a convolution is explained in depth in [23][24][25].

For simplicity, a Sobel 3x3 edge detector was investigated first because it returns a quality result with minimal computations. This edge detector masks, shown in Figure 3.4, observes the neighbors within one pixel. As mentioned above, this results in a less sensitive mask and may not locate edges that are less obvious.

-1	0	1
-2	0	2
-1	0	1

1	2	1
0	0	0
-1	-2	-1

Figure 3.4 Sobel 3x3 edge detector – X and Y directions respectively

If the image is too dark or too light, a 3x3 edge detector may not be able to distinguish the lane marking from the background. By increasing the size of the mask and using more neighboring pixels, one achieves a better result. This will result in a more robust edge detector that can handle lighting changes or poorer quality lane markings.

A Sobel 5x5 edge detector, shown in Figure 3.5, is more sensitive because it uses more neighboring pixels to enhance the edges.

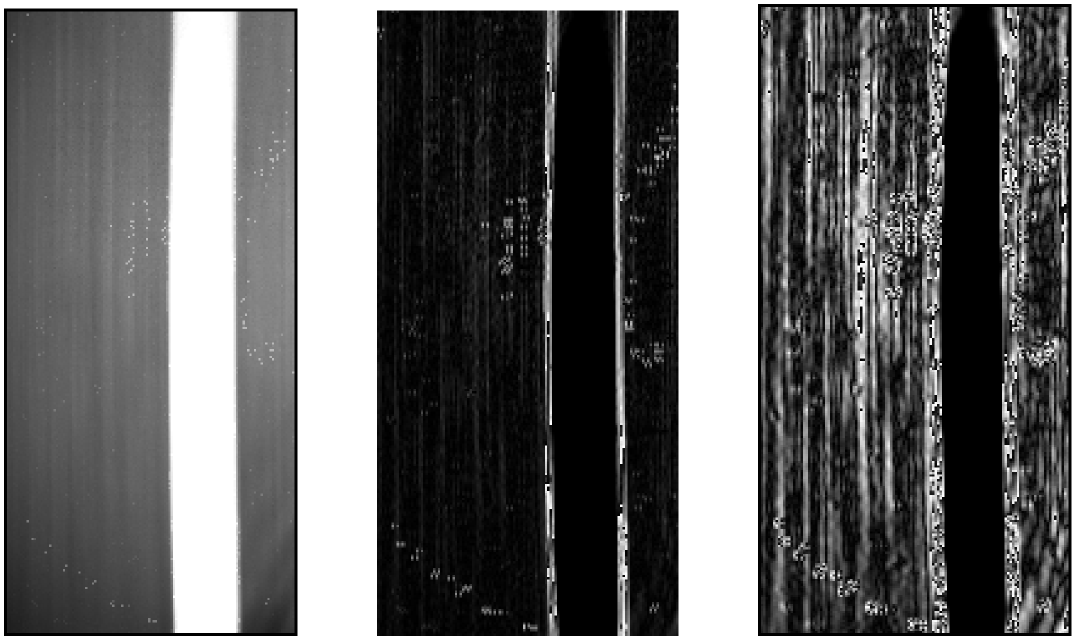
-1	-2	0	2	1
-2	-3	0	3	2
-3	-5	0	5	3
-2	-3	0	3	2
-1	-2	0	2	1

1	2	3	2	1
2	3	5	3	2
0	0	0	0	0
-2	-3	-5	-3	-2
-1	-2	-3	-2	-1

Figure 3.5 – Sobel 5x5 edge detector – X and Y directions

By increasing the size of the edge detector, there is an increase in computation time due to extra mathematical operations. Based on the road definition (from Chapter 2), the lane marking is always parallel to the direction of travel. If the camera is aligned with respect to the vehicle, the lane markings are along the Y-axis (longitudinal direction). This has a twofold benefit. First, since only edges in one direction are important, only one of the convolution masks is required and this reduces the computation time. Second, the edges that the second mask would have enhanced are suppressed and can reduce the possibility of false positive results.

An image of a white lane marking on asphalt, as well as the processed images using the Sobel 3x3 and Sobel 5x5 are shown in Figure 3.6.



(a) (b) (c)

Figure 3.6 – (a) Initial image, (b) Processed Sobel 3x3, (c) Processed Sobel 5x5

By inspecting Figure 3.6 (b) and (c), it is obvious that the Sobel 3x3 detector is less sensitive to the artifacts and minor edges that exist in the original image Figure 3.6 (a). The Sobel 5x5 image, seen in Figure 3.6 (c), has the same information that was found in Figure 3.6 (b), but enhanced all possible edges. Since all possible edges, regardless of their intensity, were enhanced due to the Sobel 5x5 edge detection mask, it was used to locate the lane marking. This prevents poorly defined lane markings from escaping detection.

3.3.3 Threshold

In order to complete the edge detection process, the edges that do not correspond to the lane marking need to be suppressed. An adaptive threshold program was used to allow each image to have a unique threshold value. In doing this, the selected threshold value is based on the pixel intensities in the image and is independent of lighting changes. To calculate a threshold value, a smoothed histogram of pixel intensity values is created from the result of the edge detection process. Figure 3.7 shows the smoothed histogram for the Sobel 5x5 result from Figure 3.6(c).

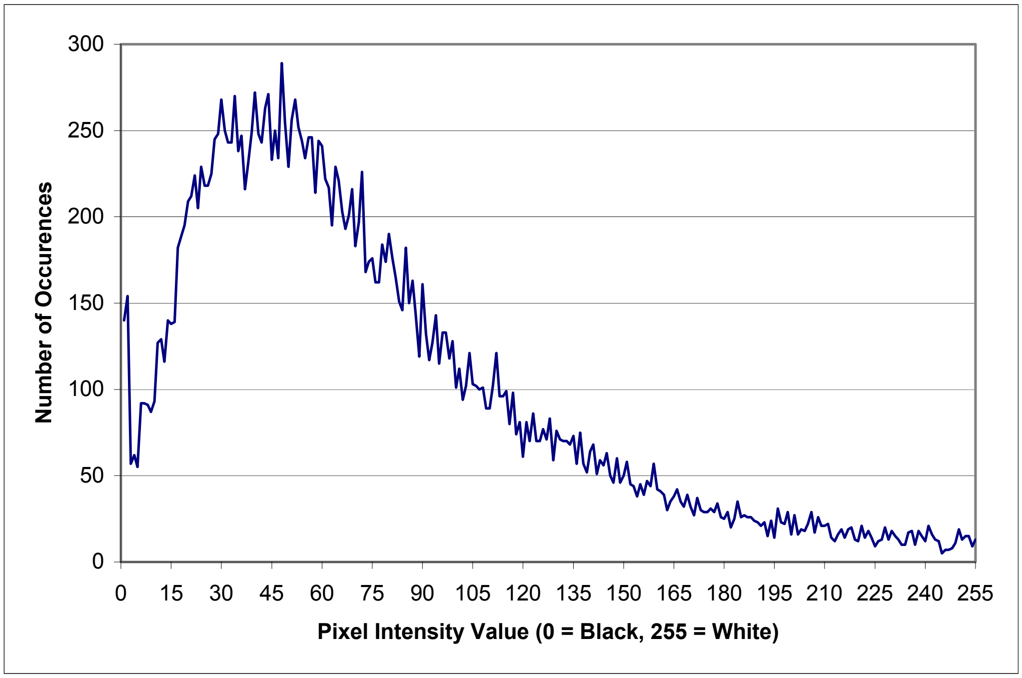


Figure 3.7 – Smoothed histogram for the Sobel 5x5 edge detected result for a single, white lane marking on asphalt

It can be seen from Figure 3.7 that most of the image is dark, but not completely black, due to the background consuming about three-quarters of the image. This results in a large peak towards the zero pixel intensity portion of the histogram. The lane marking edges, as well as the road artifacts, range widely in their pixel intensity values, but all are greater than zero. Due to this phenomenon, there is one significant peak, which is assumed to be the mean intensity level of the distribution. Examining the pixels to the left of the maximum peak, the value that reflects 95 percent of the number of occurrences between the maximum peak value and zero can be determined. In order to determine how far to the right of the maximum peak value to choose the threshold value, the difference between the value of 95 percent of the pixels between the maximum peak and zero is added to the maximum peak pixel intensity value. This gives the corresponding symmetrical 95-percent pixel value to the right of the maximum peak, shown in Figure 3.8.

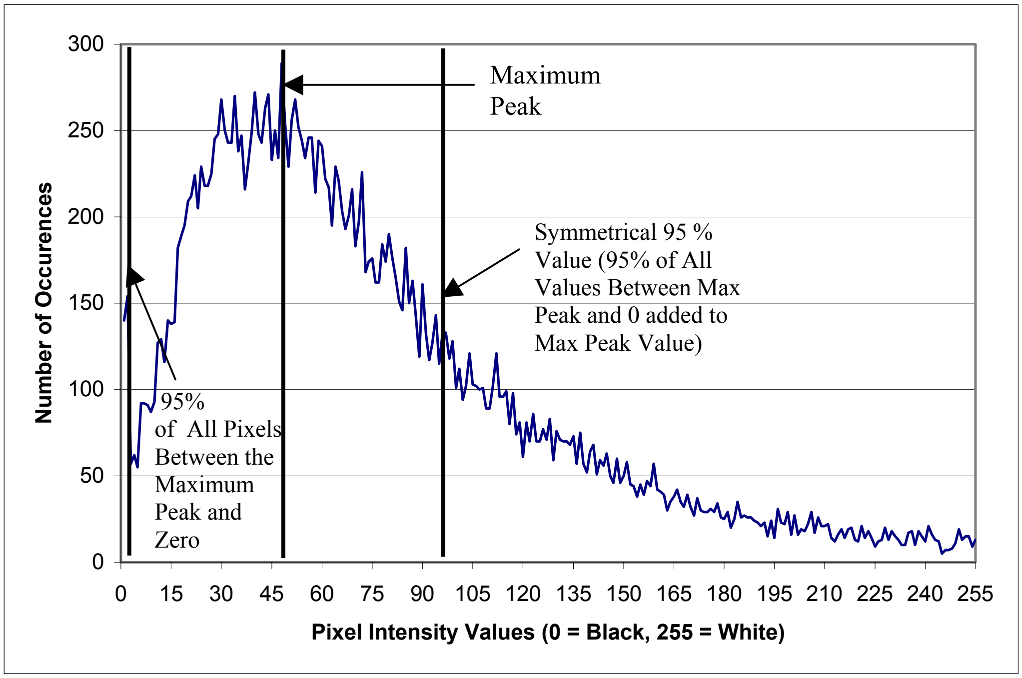


Figure 3.8 – Obtaining the threshold value

For Figure 3.8, the Maximum Peak value was determined to be 48 and the 95-percent pixel value is 2, with their difference being 46. Taking the maximum peak value of 48 and adding 46 to it, the threshold value is set at 96. The threshold value allows some of the pixels to be suppressed. In order to do this, each pixel intensity value is examined. If the pixel value is less than the determined threshold value, it is reset to a zero or black pixel. Any value above the threshold value, is set to 255 or white pixel.

Figure 3.9 shows the result of applying the threshold value to the Sobel 5x5 image used in Figure 3.6.

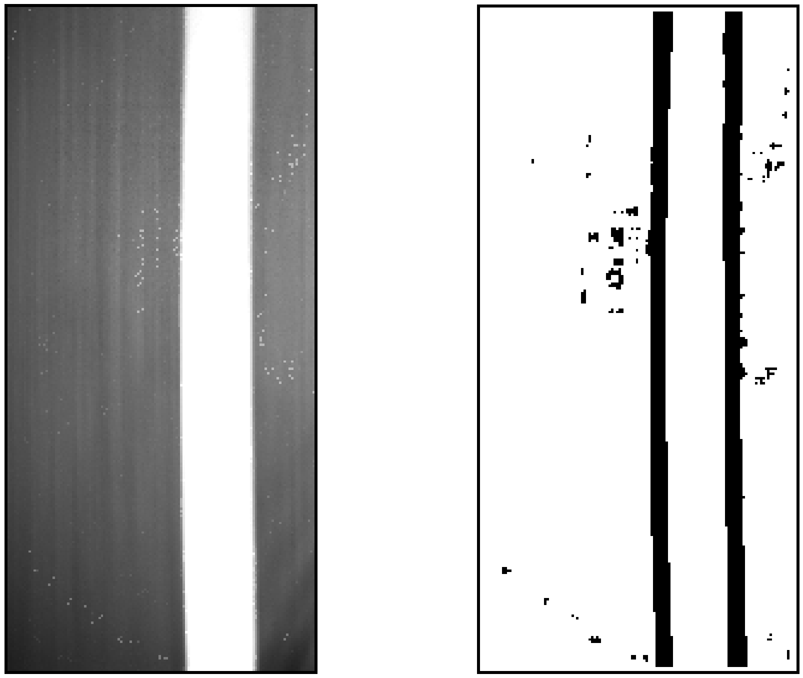


Figure 3.9 – Original image and images after applied threshold – pixel values for the processed images have been inverted (white pixels have been converted to black and vice versa) for ease of viewing

3.3.4 Hough Transform

Now that the image contains binary pixel values for black (0) and white (1), the program must detect the location of the lane marking. Due to the simplicity of the object and the fact that it consists of straight lines in a known orientation, a Hough Transform [26] is used. After the edge detection is completed and the threshold has been applied, the Hough Transform determines if each white pixel is part of a line. Since the orientation of the lane in the image is known (vertical as shown in Figure 3.9), the algorithm can be restricted to search for lines parallel to each other representing the left and right edge of the lane making in that specific orientation. This reduces the amount of computations required to locate the lane marking, and insures that there are fewer false detections.

Once all lines have been located using the Hough Transform, it can be determined which two lines are valid. In order to decide this, the width of a lane marking and the size of each pixel are required. Because these parameters are known it is possible to determine which two lines are most likely the edges of the lane marking. The center of the lane marking is the midpoint of the two valid lines. The midpoint of the lane marking is required, in conjunction with DGPS, to accurately locate the center of the lane marking as a single point in a global coordinate frame. Figure 3.10 shows the results of the Hough Transform on the threshold image shown in Figure 3.9.

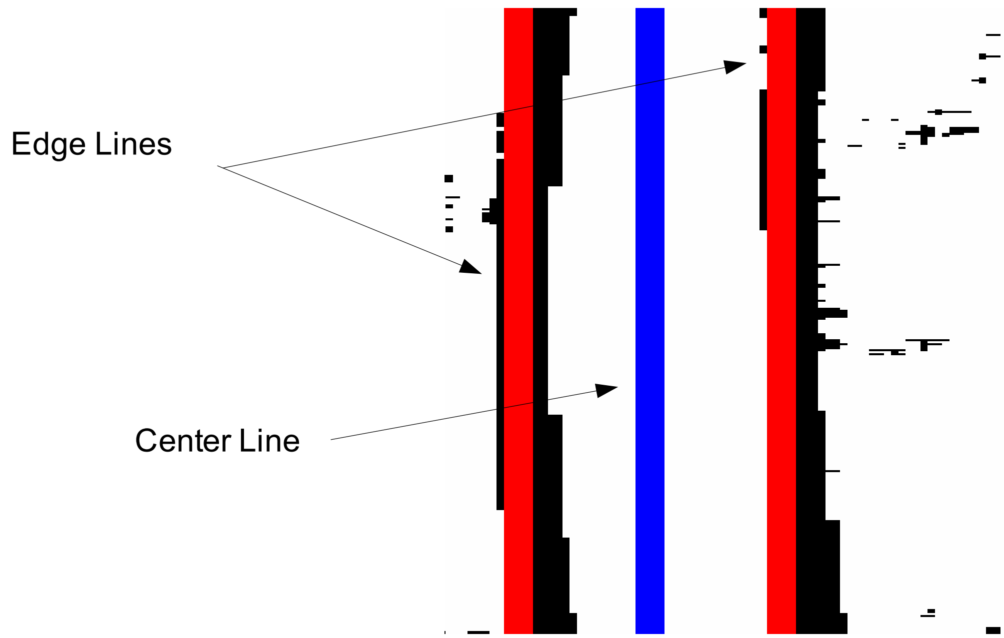


Figure 3.10 – Hough Transform result

The red lines represent the location of the edges found using the Hough Transform and the blue line represents the midpoint of those lines, or the center of the lane marking.

3.3.5 False Negatives and False Positives

As with any computer vision-based system, there are circumstances where the system has difficulty. When these situations occur, the result is often degraded accuracy. In the best case, the vision system does not return a solution (false negative) even though a lane marking is present. This can happen when the entire lane marking is not in the image, or the system cannot extract the edges in the image (i.e., fading paint or undefined paint boundary). The worst-case scenario returns a false positive position. This can occur when the system mistakes the boundaries of the lane marking for a shadow or a misplaced lane marking during re-striping.

In the best-case scenario, the system fails to return a valid position, or results in a false negative. Typically, this is because the entire lane marking is not captured by the image. However, there are cases when a lane marking exists, but the system cannot locate it.

Figure 3.11 shows an example when a portion of the lane marking is outside of the field of view of the camera. In this case, the system can only assume where the center of the lane marking is based on the amount of visible lane marking. Since accuracy is the main focus, the system does not assume where the center may be; instead, it ignores the image and proceeds to the next one. Ignoring this situation decreases the number of DGPS positions that can be used to create a geospatial database, but prevents geometrical inaccuracies due to false assumptions.

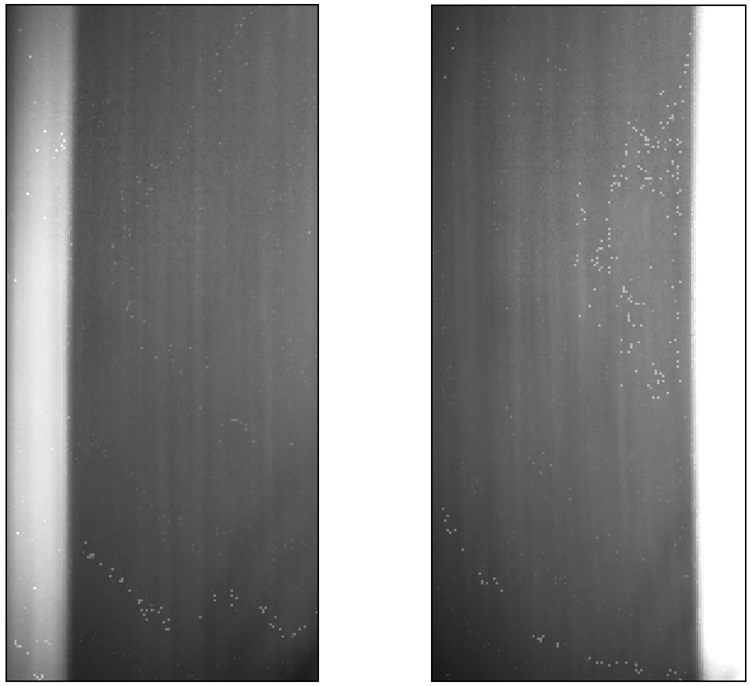
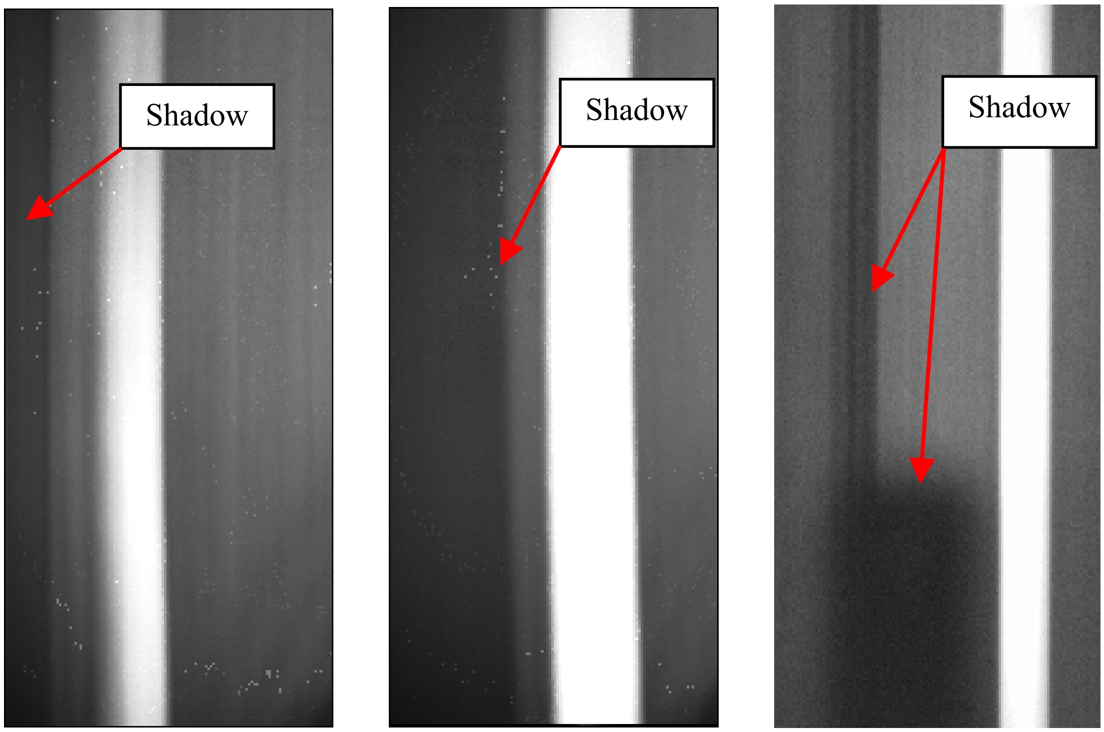


Figure 3.11 – Lane marking partially outside camera field of view

False positives pose a different problem. In these cases, the location of the lane marking is identifiable, but is either erroneous or in the wrong spot. One situation that can produce a false positive is a shadow. Shadows can either obscure a portion of the lane marking or artificially create an edge. Direct control of the illumination helps to reduce this problem, but there are times when the situation exists as shown in Figure 3.12.



(a) **(b)** **(c)**

Figure 3.12 – Shadows visible in camera image

All three images in Figure 3.12 show a lane marking as well as a shadow. Even with the correct placement of an external light source, shadows can occur. Objects such as curbs or guard rails or parts of the data collection vehicle can introduce shadows to the scene. Careful placement of the light source can eliminate most shadows. Figure 3.13 shows a set of lane markings that can cause a problem for a vision system.

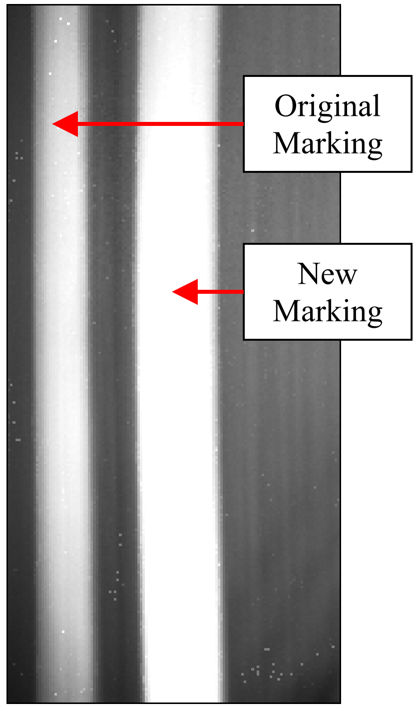


Figure 3.13 – Double lane marking

Figure 3.13 shows a double lane marking, but not by design. This occurs when the road is re-striped and the new lane marking does not overlay the original marking. When this happens, the location of the center of the lane marking is not accurate. The original marking can cause the vision system to offset the position of the lane marking. However, the two lines are close to each other and therefore the offset is relatively small and is not a significant problem.

Another problem occurs when collecting data on a road with crosswalks or stop lines at an intersection. These types of markings are designed for pedestrian traffic. The crosswalk is the area that the pedestrians should use to cross the road and the stop line is a painted line along the road to signal where the drivers should stop to allow the pedestrians room to cross. These markings are shown in Figure 3.14.

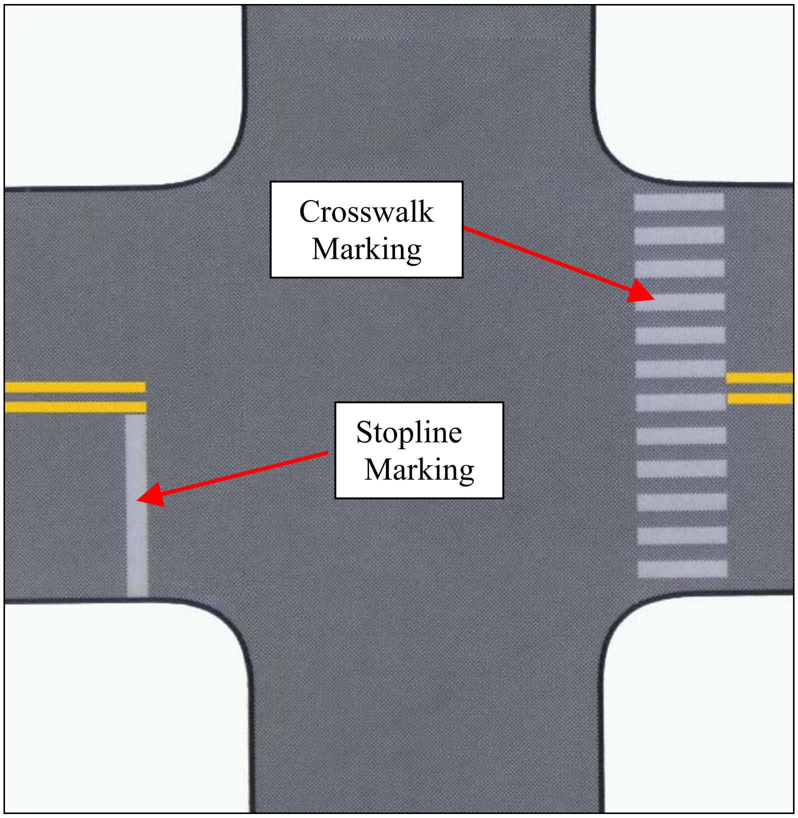


Figure 3.14 – Crosswalk and stop line

If the crosswalk or stop line is in the field of view of the camera, especially inline with the lane markings, the vision system gets an image where it is almost entirely white. This situation is shown in Figure 3.15.

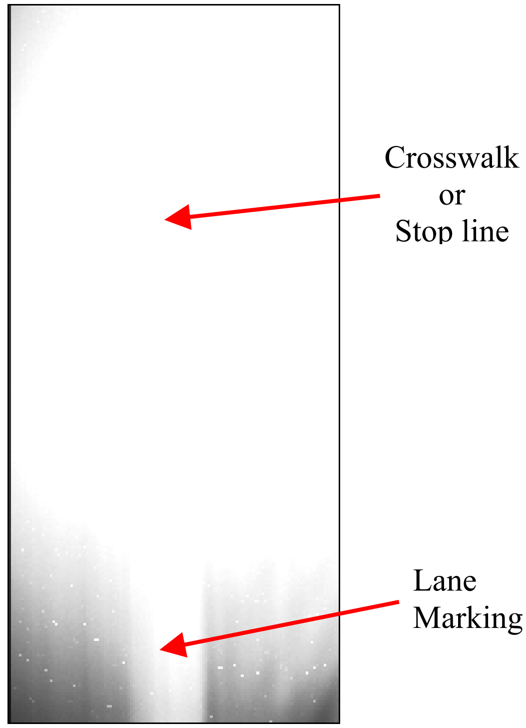


Figure 3.15 – Crosswalk or stop line

Figure 3.15 shows a portion of the lane marking with most of the image consisting of the crosswalk paint. Typically, this only appears in a single image for each occurrence of a crosswalk or stop line. In such cases, the data point does not get recorded.

There is also the situation where the lane marking is augmented. Botts' Dots, used extensively in California, are raised reflectors that allow drivers to see the lane markings at night or in the rain. Due to their reflectivity and circular shape, they may cause the computer vision-based system to incorrectly locate the lane marking. The author recognizes that this is a potential problem, but this type of lane marking was not available for testing during the research project as snowplows will quickly destroy any raised pavement marking.

3.4 Global Coordinates

Once the lane marking location in the image has been determined, it is important to know where the lane marking is with respect to a global positional reference frame. In order to determine this, the camera position and orientation, with respect to a DGPS unit, is required.

3.4.1 DGPS Adjustment

There are five parameters that are required in order to compute the transformation from camera coordinates (pixels) to local global coordinates (meters). The result of the Hough Transform provides the position of the lane marking in pixel coordinates and DGPS provides the position of the DGPS antenna in global coordinates. That accounts for four of the required parameters: local position (x, y) and DGPS position (x, y). The fifth parameter is the heading of the vehicle with respect to the global coordinate system. Heading is computed based on previous DGPS positions.

In order to convert from the local coordinates (pixels) to global coordinates (meters), the size of each pixel must be known. This parameter is determined prior to data collection. It is a simple procedure requiring an image of an object of known size in the global coordinate system. By measuring the size of the object in the image in pixels and having the known size in meters, the size of a pixel can be determined.

Using the size of a pixel in meters and knowing the position of the line in pixels, the position of the lane marking can be determined in meters. By knowing where the camera is with respect to the DGPS antenna, the position of the lane marking can be determined in the global coordinate frame.

3.4.2 Quantity of Collected Data

Traditionally, when using a camera to collect data, the image is stored for post processing. This enables the data collection program to run at a reasonably fast rate, but requires a large amount of storage space. Collecting 128 pixel x 240 pixel, 8 bit images at 30 Hz (30 frames per second) requires one megabyte (MB) of space per second. Collecting data for one hour produces 3600 MB of image data. Storage quickly becomes a problem. However, if the image is processed during data collection, there is no reason to save the image. Data is saved only when the image processing portion of the software locates the center of the lane marking. In addition to saving the processed position of the lane marking in the image, raw DGPS data is saved to a text file in ASCII format as shown in the data string below.

GPS Time, GPS X, GPS Y, GPS Height, GPS Quality, Vehicle Heading, Vehicle Speed, Processed X, Processed Y

These items are defined as follows:
GPS Time – The DGPS unit time
GPS Latitude, Longitude, Height – The location of the DGPS antenna in three dimensions
GPS Quality – The quality of the differential solution as a numerical value
Vehicle Heading – The angle of the vehicle with respect to North
Vehicle Speed – The vehicle speed as calculated by DGPS
Processed X, Y – A single adjusted value of the DGPS position based on the Image Processing Result explained above

Data is only saved if the vision-based system determines the position of the lane marking. If there is no lane marking in the image, the system doesn't record the data string and processed position.

3.5 Real-Time Data Collection Approach

At highway speeds of 88.5 kph (55 mph), a vehicle will travel 24.6 meters (80.7 feet) in one second. At that speed, a camera capturing images at 30 Hz will capture nearly three feet of new data per image. The Trimble MS750 DGPS unit provides non-extrapolated position data at 10 Hz. Therefore, collecting data at 30 Hz does not provide any information that is useable since 2/3 of the data does not have an updated position. Currently, collection and processing takes 78 milliseconds, or can run at 12.75 frames per second (fps). Therefore, data collection is restricted by the rate of the DGPS data availability, 10 Hz. Figure 3.16 shows the position of the camera and its field of view at each DGPS position update where Δt_x is equivalent to 0.1 second. This results in the camera image capturing a new data point every 2.5 meters (8.1 feet) when traveling at 88.5 kph (55 mph).

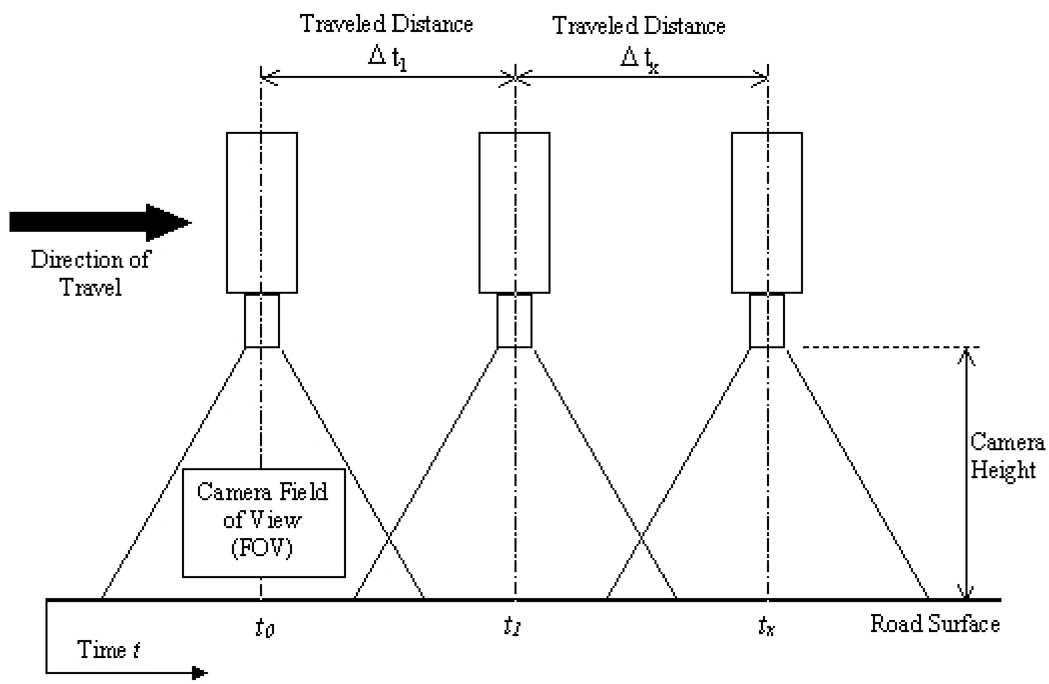


Figure 3.16 – Camera images based on dynamic vehicle

Chapter 4
Post Processing and Database Creation

Even though the data can be collected in real-time, there is still the need for some post processing work. Focusing on a two-lane road, one lane in each direction, the data collected can be reduced to the right fog line in each direction as per our definition of a road. This data, collected in real-time, consists of the DGPS position adjusted to the center of the fog line. The text files of DGPS positions are stored with a filename that encodes information about the road and is needed for post processing. Using that information, in addition to the number of lanes and the road's name, the files can be processed and a geospatial database can be created.

4.1 Software

4.1.1 Filename and Data Files

As mentioned earlier, the filenames for each run of data collected contain information about the enclosed data. Each filename is divided into four parts: Road Type (RT), Data Type (dt), Direction (d), and File Number (#) as shown in Figure 4.1.

RT_dt_d_# . txt

Figure 4.1 – Filename format

Each part of the filename has multiple options that define the road for the post processing software. These choices are shown in Table 4.1.

Table 4.1 – Filename options

<table>
<tr><th>Road Type
(RT)</th><th>Data Type
(dt)</th><th>Direction
(d)</th><th>File Number
(#)</th></tr>
<tr><td rowspan="2">Interstate
(IN)</td><td rowspan="2">Center Line
(cl)</td><td rowspan="2">North
(n)</td><td>1</td></tr>
<tr><td>2</td></tr>
<tr><td rowspan="2">State Highway
(SH)</td><td rowspan="2">Lane Boundary
(lb)</td><td rowspan="2">South
(s)</td><td>3</td></tr>
<tr><td>:</td></tr>
<tr><td rowspan="2">County Highway
(CH)</td><td rowspan="2">Road Shoulder
(rs)</td><td rowspan="2">East
(e)</td><td>:</td></tr>
<tr><td>:</td></tr>
<tr><td rowspan="2">Residential/Commercial
(RC)</td><td rowspan="2"></td><td rowspan="2">West
(w)</td><td>:</td></tr>
<tr><td>inf</td></tr>
</table>

There are two basic types of public roads, a highway and all of the other roads. Highways are major roads within cities or linking cities, which can have multiple lanes of traffic, and are designed for high-speed traffic. There are sub-categories for highways that are listed in Table 4.1. They are interstate, state highways, and county highways.

Residential or commercial roads are smaller volume roads that are found in urban or suburban areas. They tend to have many intersecting roads with stop signs and/or traffic signals. These roads typically have pedestrians moving across or along them, which demand extra caution on the part of drivers. Residential or commercial roads have typical speed limits of 48.2-72.4 kph (30-45 mph) and may not have fog lines. These types of roads are less of a concern here due to the limited number of lane departure fatalities and abundance of physical references, which facilitate snowplowing in low visibility conditions. However, these are valid roads and the option for adding them is included for future use. The focus described herein is on the highway category.

The *data type* (Table 4.1) is used to allow the post processing software to determine what the enclosed data represents. The data type for the vision-based data collection will always be *lb* (i.e. for lane boundary). The inclusion of *cl* (i.e. centerline) and *rs* (i.e. road shoulder) allows flexibility in the collection software. Depending on the data type, the post processing software will process the data differently.

The direction utilizes the four major compass directions: North, South, East, and West. All highways in the United States use one of these four compass directions to indicate their general direction of travel.

Since there are never more than two fog lines per direction, the maximum number of files in each direction will be two. However, for flexibility, this number can be increased.

Every road has a name and it is an important identifier for distinguishing one road from another. The filename fields were chosen because they give information about the actual road, whereas, the name of the road does not. Road names are not always static. If the filename uses the road name, data collection would need to stop and restart at each road name change.

4.1.2 Post Processing Collected Data

Standardized filenames allow for post-processing simplification. Software can search through a specified folder and group all of the files according to their filenames. All similar road types are grouped together and are arrayed by the data type, direction, and file numbers.

Based on the road definition, the files can give insight into the nature of the road. Table 4.2 shows six arbitrary files of collected data. They have been grouped by their filenames.

Table 4.2 – Example – grouped files

Road 1	Road 2
CH_lb_e_1.txt	IN _lb_e_1.txt
CH_lb_w_1.txt	IN _lb_e_2.txt
	IN _lb_w_1.txt
	IN _lb_w_2.txt

By observing the filenames for each road in Table 4.2, it is possible to determine the basic road type. If the data in Table 4.2 was collected using the vision-based system, then *Road 1* is an undivided county highway (CH) and *Road 2* is a divided Interstate (IN). *Road 1* is undivided because there are two files in opposite directions. If just the fog lines are collected, as in the vision-based data collection method, that reveals that each file is the rightmost fog line. Figure 4.2 shows where each file for *Road 1* would be collected.

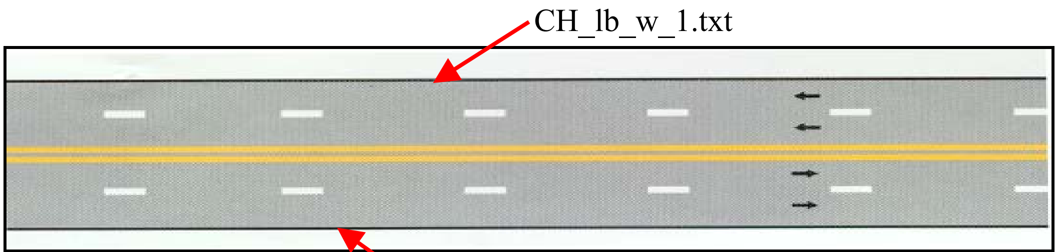


Figure 4.2 – Data file positions for *Road 1*

In the case of *Road 2*, there are four total files with two files per direction. This would mean that there is some form of road divider present. The road divider could be anything from a jersey barrier to a grass ditch or a median. Since the road divider width is an unknown, both fog lines must be collected in each direction. Figure 4.3 shows the placement of the files for *Road 2*.

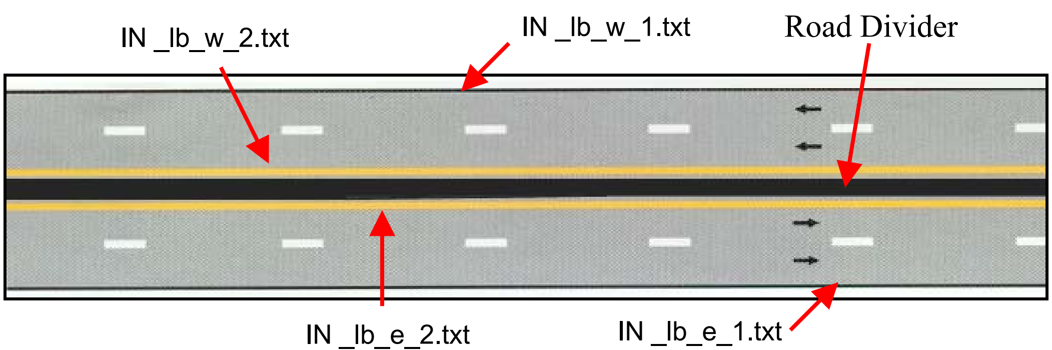


Figure 4.3 – Data file positions for *Road 2*

Once all of the files are grouped, they can be processed into a geospatial database. In order to do this, the total number of lanes is required. For example, Figure 4.2 has four lanes, two per direction. Figure 4.3 also has four total lanes separated by a road divider. This results in two lanes and two fog lines in each direction. When a road divider is present, each set of two fog lines is processed separately. Table 4.3 shows the input requirements needed per road.

Table 4.3 – Input information for Figures 4.2 and 4.3

Road	Input File 1	Input File 2	# Of Lanes (NOL)
1	CH_lb_e_1.txt	CH_lb_w_1.txt	4
2	IN_lb_e_1.txt	IN_lb_e_2.txt	2
2	IN_lb_w_1.txt	IN_lb_w_2.txt	2

Lane width has not been mentioned because it varies from state to state. In Minnesota, the standard width of an interstate, state highway, and county highway is 3.7 meters (12 feet). However, this is not always the case. A 3.0-meter (10 feet) wide lane is also common, but experience has shown that any width from 2.4 meters (8 feet) for a residential road to 4.0 meters (13 feet) for a county highway can exist. While lane width is an important attribute for a geospatial database, it is not always possible to measure a lane in order to ensure its accuracy. Because of this fact, it must be possible to measure the lane's width in another fashion. This can be done with another camera observing the scene from another angle or using satellite-based or photogrammetry-based images. However, using the method described herein, the extreme physical boundaries of the lane are known as well as the number of lanes between these boundaries, once the data collection for the fog lines has been completed. It is also known, based on the road definition stated in Chapter 2, that all of the lanes are effectively parallel. This provides enough information to calculate the lane width and, subsequently, create the intermediary lanes and boundaries described in the following section.

4.1.3 Lane Width Calculation

If the distance between the two fog lines is known, the lane width is found by dividing that distance by the number of lanes (NOL). By sampling the collected data, the distance between the fog lines can be computed. One major problem arises when sampling data. This occurs when there is a lane addition or reduction on the road (adding or removing a lane along the road). An incorrect sampling may hide the beginning of the addition or reduction. By computing the distance between all of the DGPS position points in the data files, the start of the addition or reduction can be determined.

Since there are two fog lines, which are parallel to one another, it is possible to compute the distance of a point on one fog line to the other fog line. Choosing which file is used for line segments or points is an arbitrary choice. Figure 4.4 shows a single point, (x_0, y_0) and two points ((x_1, y_1) and (x_2, y_2)) that construct the line segment. The perpendicular distance $\boldsymbol{d}$ is shown between the single point and line segment and the vector $\boldsymbol{r}$ represents the distance of the single point to a point on the line segment. The vector $\boldsymbol{v}$ is an arbitrarily positioned vector perpendicular to the line segment.

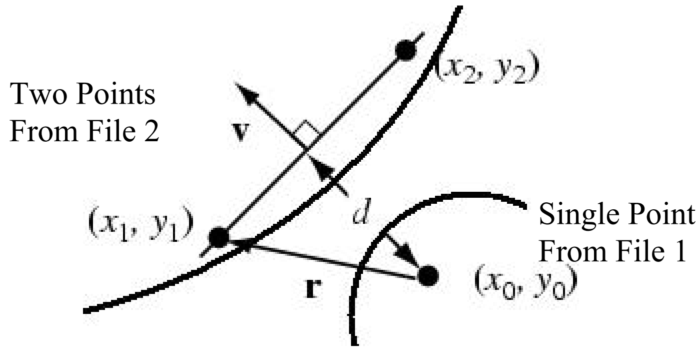


Figure 4.4 – Perpendicular distance between a point and a line segment. Please note that either file can be *File 1* or *File 2*. Because the distance between the two fog lines is desired, the order of the files is irrelevant.

The equation of a general line segment in the slope-intercept form is

$$y = -\frac{a}{b}x - \frac{c}{b} \tag{1}$$

The vector that is perpendicular to this line is then

$$\mathbf{v} = \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} y_2 - y_1 \\ -(x_2 - x_1) \end{bmatrix} \tag{2}$$

The vector ***r***, which is the vector between the single point (x_0, y_0) and the line segment, is

$$\mathbf{r} = \begin{bmatrix} x - x_0 \\ y - y_0 \end{bmatrix} = \begin{bmatrix} x_1 - x_0 \\ y_1 - y_0 \end{bmatrix} \tag{3}$$

By projecting ***r*** onto ***v***, the distance d is computed.

$$d = \frac{|\mathbf{v} \bullet r|}{|\mathbf{v}|} = \frac{(y_2 - y_1)*(x_1 - x_o) - (x_2 - x_1)*(y_1 - y_0)}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \tag{4}$$

Choosing the single point from one of the files and locating the two points that it lies between can reliably compute the perpendicular distance. Once each distance is computed and the number of lanes (NOL) is known, the lane width can be determined.

$$lane\_width = \frac{d}{NOL} \tag{5}$$

As mentioned earlier, most highways in Minnesota use a 3.7-meter (12 feet) lane and some use a 3.0-meter (10 feet) lane. Occasionally, the lane width is neither of these choices. The lane width on a highway is generally never less than 3.0 meters (10 feet) or greater than 3.7 meters (12 feet).

Sudden lane additions and reductions can cause additional problems. If, during the course of data collection, a lane is added or removed, a slightly different method is employed. The computations discussed earlier for lane width calculations are still valid, but some conditions for the lane width final decision are required. If the computed lane width is less than 3.0 meters (10 feet) wide or greater than 4.0 meters (13 feet) wide, a lane has been added or removed, respectively. It is unlikely that the width of a lane will suddenly change; there is usually a transition zone. As soon as this is detected, a single lane is added or subtracted and the lane width is recomputed. This process can run iteratively until a result is achieved given that the width of a lane is typically no smaller than 3.0 meters (10 feet) and no wider than 3.7 meters (12 feet).

4.1.4 Database Files

At this point, the distance between the fog lines and the number of lanes are known. Using the assumption that all lanes are parallel, it is possible to copy the input files and offset the data by the computed lane width. This results in a number of lane boundary files originally derived from the fog line (a lane boundary) and centerline files. Centerlines are located mid-way between two lane boundaries. These are found by creating files that have been offset one half of the lane width from each lane boundary.

Finally, the data type, *road shoulder* can be created. As defined earlier, road shoulders are the boundary of the drivable surface. Experience has shown that this can be a distance from 0-3.7 meters (0-12 feet). The width can change suddenly and this can be problematic for an automated measuring system. The road shoulder permits a driver, using a HUD, to see where the road surface actually ends and allows the radar-target filter (RTF) to exclude any radar target beyond that boundary. For lane departure prevention, the road shoulder's exact size is less important. Therefore, the size of a road shoulder is assumed to be 1.8 meters (6 ft) [27]. Six-foot road shoulders were chosen because they are Mn/DOT's minimum allowed road shoulder or "clear zone" width. This value was chosen in order to give an adequate estimation of the extent of the road. Again, this is not as crucial for a lane departure prevention system, but is required for the Radar Target Filter (RTF).

All of the lane boundaries, centerlines, and road shoulders have been created, but lack any attribute information that defines them. Attributes define other non-spatial properties, which remain static for the data they define. The attributes for each data type were defined in [13], with minor updates, and are shown in Table 4.4.

Table 4.4 – Data type attributes

Lane Boundary	Centerline	Road Shoulder
Road Name	Road Name	Road Name
Lane Right	Lane	Group
Lane Left	Group	Id
Group	Id	Next
Id	Next	Previous
Next	Previous	Direction
Previous	Direction	Side
Direction	Speed	
Type		
Marking		
Color		

All three data types have *Group*, *Id*, *Next*, and *Previous* attributes which define the position of each group of data within the data type. This organizes the data based on the direction of travel. *Road Name* and *Direction* also make an appearance in each data type. This is supplied by the input file's filename.

Lane boundaries exist between two drivable lanes. Therefore, there exists a lane to the left and right of each lane boundary marking. The *Type* refers to what type of lane exists on either side of the lane boundary and is useful for the RTF. There are three options: there is no drivable lane on one side, both sides have drivable lanes in the same direction, both sides have drivable lanes in opposite direction. The *marking* and *color* explain the actual lane marking on the road: double lines, single line, skip line, yellow or white colored lines. These attributes allow a VES to draw representations of the lane boundaries that are similar to the actual lane markings.

Each centerline has a unique numerical *Lane* identifier. The rightmost lane is set to one and increases when moving to the left. This is true regardless of the direction of travel. The *Speed* attribute is the posted speed limit applied to the road.

Road Shoulders appear on one or both sides of a road and are captured in the S*ide* attribute (For each database created in the IV Lab, a road shoulder entity, which is used by the RTF, is created regardless of whether or not an actual road shoulder exists. The road shoulder is not used for anything other than the RTF). If a road has road shoulders, there always exists a road shoulder on the right side of the road, but if there is a road divider of any sort, there will be a road shoulder on the left in addition to the one on the right side of the road.

Nearly all of the attributes are determined by the filename from Figure 4.1 and passed to the geospatial database creation software. All of the attributes can be automated and assembled prior to the geospatial database creation and passed to the geospatial database creation software.

At the completion of the attribute addition stage, each road can be processed as a separate entity unto itself or grouped together. For example, using the information from Table 4.2, there are two possibilities for the final geospatial database. Three geospatial databases can be created: one for *Road 1* and two for *Road 2* because of the road divider, or one geospatial database containing both sets of roads. This is left to the discretion of the mapmaker.

An extra option has been added to facilitate data modification. There is a second set of files that can be output from the software. These files are constructed in a format for ArcView (http://www.esri.com). ArcView is a popular GIS software package that many DOTs use. The second set of files created allows the data to be imported and retain all of the attributes previously assigned. This can prove useful when adding a road to an existing geospatial database or when a road has undergone construction and has been modified. These sets of files are not needed for the creation of the geospatial database, but are present to allow another means of data manipulation. Once the data is in ArcView, scripts have been created to export the ArcView data back into geospatial database files.

Chapter 5
Experiments

Experiments were designed to test the accuracy of the vision-based mapping system on actual roads. In order to reduce the amount of time required for data collection, the system must collect an accurate lane marking position in a single pass. There is also a safety concern since the best time to collect data is during the night, when illumination can be controlled. While this tends to reduce traffic load on the road, it also reduces visibility. A data collection vehicle traveling at less than posted speeds increases the possibility of a collision with another vehicle. Since roads that will be digitized using this method are open to the public, care must be taken to ensure that the road-digitizing vehicle can move at speeds, which will have little effect on other normal traffic.

For all experiments, the data collection vehicle was the SAFEPLOW, an instrumented 1998 International model 2450 truck outfitted with strobe lights. These lights increase the visibility of the vehicle while collecting data. A Trimble MS750, which is a dual-frequency carrier phase, real-time kinematic, DGPS unit was used for all data collection. This unit has the ability to compute a new position at 10 Hertz (Hz) and has a static accuracy of 2-5 cm and a dynamic accuracy of 5-8 cm [28], both at $\pm 1\sigma$.

Since the DGPS updates at 10 Hz, the collection and processing of each image should be completed before the next DGPS update. As the data collection vehicle speed increases, the distance between successive DGPS points increases. If the system cannot keep pace with the DGPS updates, the resulting data may not accurately capture the road geometry.

5.1 Experimental Setup

As mentioned earlier, a Pentium III, 1.26 GHz dual processor computer running Windows 2000 Professional was used as the data collection computer. The two inputs to the computer included the DGPS information and the image capture source.

The DGPS information from the DGPS unit is captured in latitude and longitude and passed to a PC104 computer running the QNX/Neutrino real-time operating system. There the latitude and longitude information is converted into a local state plane coordinate system as per the geospatial database described in [13]. A diagram of this is shown in Figure 5.1. The Windows computer requests the DGPS information from the QNX machine through an Ethernet connection.

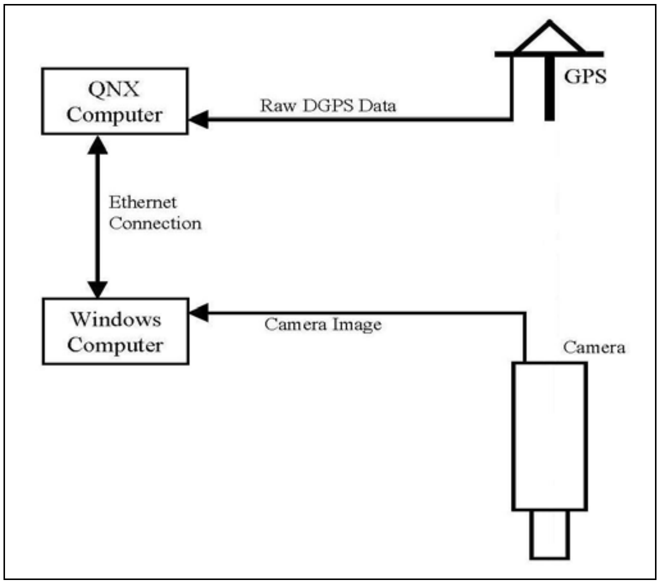


Figure 5.1 – Experimental setup

The camera used for these experiments was an iBot2 USB 2.0 web cam manufactured by Orange Micro, Inc. (http://www.orangemicro.com) shown in Figure 5.2.

Figure 5.2 – Orange Micro iBot2 web cam

This camera requires a USB 2.0 connection so there was no need for an image capture board.

As mentioned in Chapter 3, the vision system locates the position of the lane marking in the camera coordinate frame (pixels) and must convert the result to local global coordinates, the Minnesota State South Plane in this case. In order to do that, the position of the DGPS antenna with respect to the camera must be known. To simplify this constraint, a mount was designed so that the phase center of the DGPS antenna and the center of the camera lens were collinear. Figure 5.3 shows the vision system mount attached to the front of the SAFEPLOW.

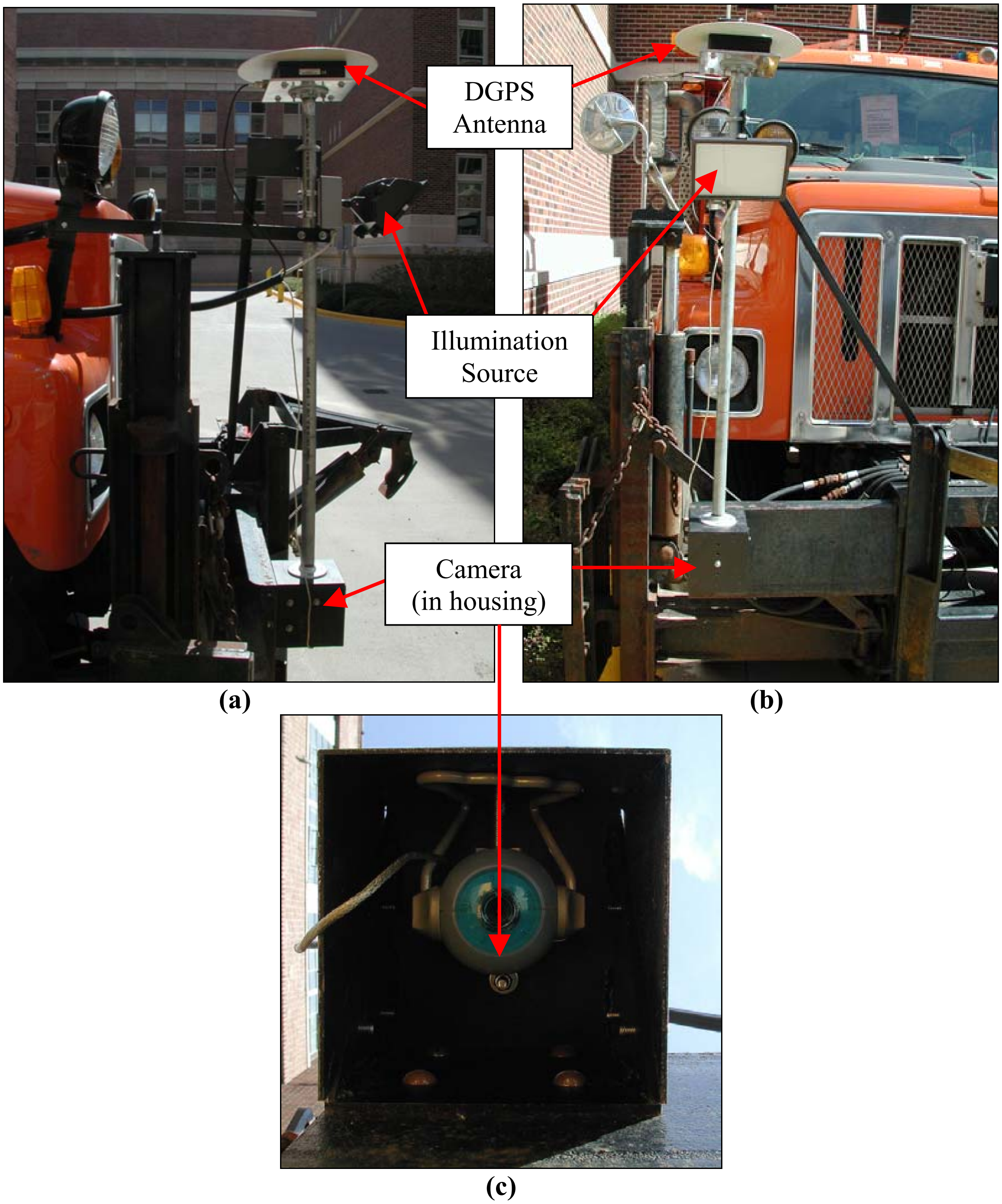


Figure 5.3 –Vision system mount – (a) passenger side view, (b) front side view, (c) view of mounted camera (from below)

Notice the mount is on the passenger side of the vehicle. In this position the rightmost fog line can be collected. However, this position makes it difficult for the driver of the vehicle to know where the lane marking is with respect to the camera. This can be seen from the driver's perspective in Figure 5.4.

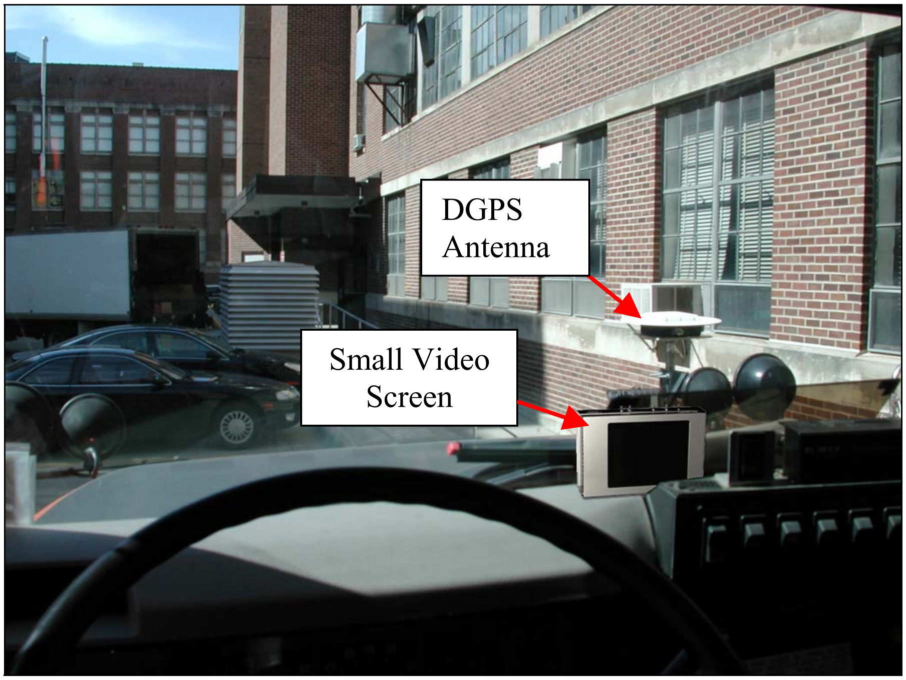


Figure 5.4 – Vision system mount – driver's view

A small video screen, shown in Figure 5.4, was provided to the driver so that he or she could see what was in the camera's field of view. The video screen was used in order to train the driver as to where he or she should position the vehicle to capture the lane marking.

During the experiments, it took the driver a short time to recognize where to position the vehicle so the video screen was not a necessity. Please note that safely controlling the vehicle in traffic had the highest priority and maintaining the lane marking in the image was not. However, it was requested that the drivers do their best to keep the lane marking in the image.

5.2 Validation Method

Each of these roads required an accurate set of data with which to compare the vision-based data collection system. Since the vision-based system is designed to accurately determine the lane marking position, its accuracy should be compared against the most accurate data available. Presently, photogrammetry is the most widely used data with good accuracy. Mn/DOT provided photogrammetry data for State Highway 252 that was digitized in 2003 and meets the National Standard for Spatial Data Accuracy (NSSDA) horizontal accuracy of 30.5 cm (12 inches). However, the vision-based system uses a DGPS unit that has static accuracy from 2-5 cm (0.8-2.0 inches) and a dynamic accuracy of 5-8 cm (2.0-3.1 inches) both at $\pm$ 1σ. Therefore, comparing the vision-based system results against photogrammetry is not a true measure of the mapping system's accuracy. As a result, another set of accurate data was needed to compare against the vision-based system.

Ideally, the accurate set of data used to compare the vision-based system results should be an order of magnitude better than the accuracy of the DGPS unit: 2-5 cm (0.8-2.0 inches) static and 5-8 cm (2.0-3.1 inches) dynamic both at $\pm 1\sigma$. At this time, the DGPS accuracy when statically acquired is the most accurate; the vision-based system will be compared to it. In order to accomplish this, each route used for validation was mapped using static DGPS measurements. The SAFEPLOW was stopped at intervals along the road and the DGPS antenna was positioned over the center of the lane marking. By collecting data for a period of time (3-5 seconds at 10 Hz) and averaging that data, the true location of the lane marking was determined to within the accuracy of the DGPS unit. This data will be referred to as the validation map.

All experimental results used the Orange Micro iBot camera positioned 82.6 cm (32.5 inches) from the ground and having a 64.8 cm (25.5 inches) wide field of view. The lane marking measured width was 10.2 cm (4.0 inches).

5.3 Experimental Routes

In order to test the system, two routes were chosen and are described in detail below. These routes were chosen due to their design and because each road had been mapped previously for research projects in the IV Lab.

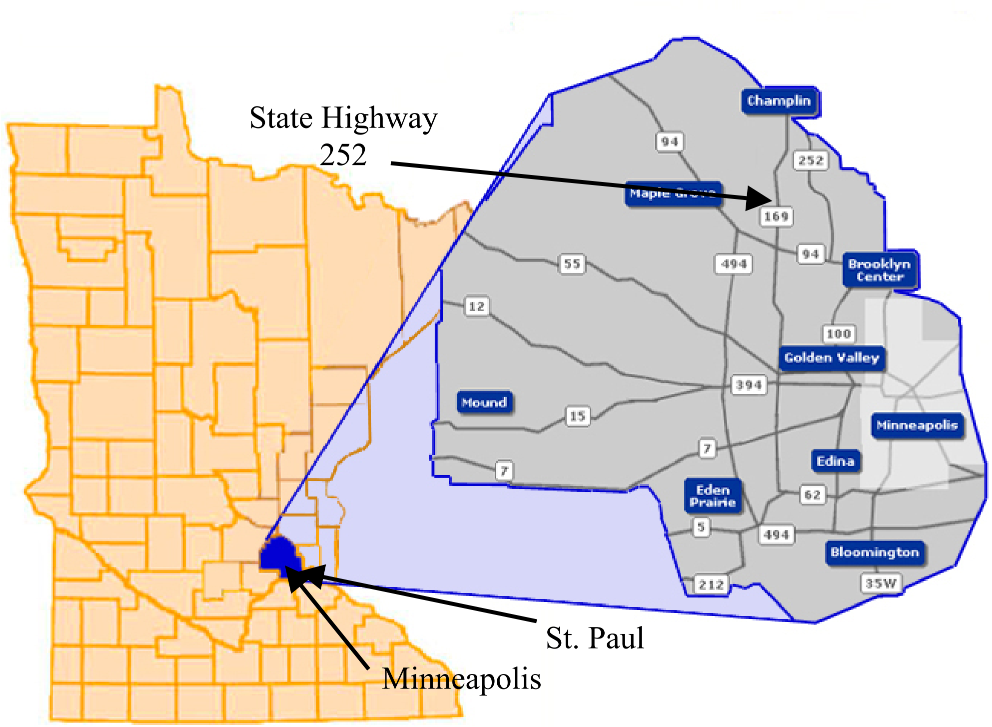


Figure 5.6 – Hwy 252– Minnesota counties with Hennepin County inset

The first route, State Highway 252 shown in Figure 5.6, is a multi-lane divided highway, which is approximately 16.1 km (10 miles) north of downtown Minneapolis. It is one of the few highways that travel through the northern suburbs of the Twin Cities. This corridor contains traffic signals and is subject to a large volume of traffic during rush hour. Highway 252 runs north and south and was used in [29] for transit buses. The length of the route is 4.0 kilometers (2.5 miles).

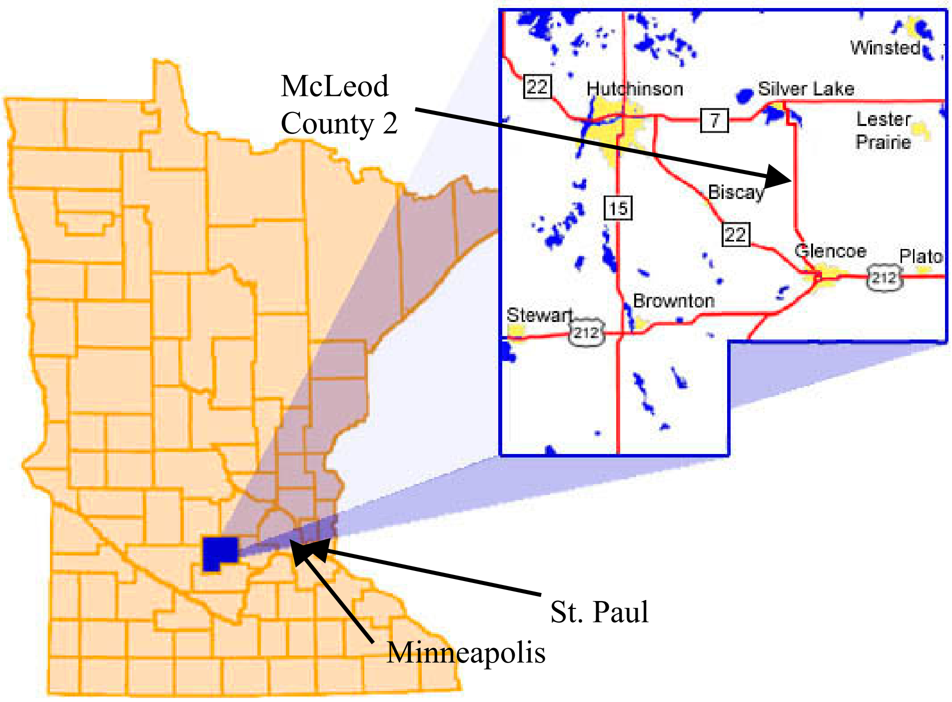


Figure 5.7 – McLeod County 2 – Minnesota counties with McLeod County inset

McLeod County 2 in McLeod County Minnesota, shown in Figure 5.7, was chosen as the second route. McLeod County 2 had been mapped in the past in order to support a snowplow stationed in McLeod County as part of a field operational test of vision enhancement systems [30] in 2001. McLeod County 2 is a two lane, bi-directional, undivided road that runs between Silver Lake and Glencoe. This particular road has a small volume of traffic, but is situated between farm fields and is subject to winds and snowdrifts. McLeod County 2 runs north and south between the cities of Silver Lake and Glencoe and is 15.3 kilometers (9.4 miles) long.

5.3.1 Highway 252 Intersections

State Highway 252 has signal-controlled intersections, all with right and left turn lanes. Some of the intersections have off- and on-ramp style turn lanes with road islands. This results in the absence of data through the intersection and adjacent to the turn lanes. Figure 5.8 shows State Highway 252 and the location of the intersections.

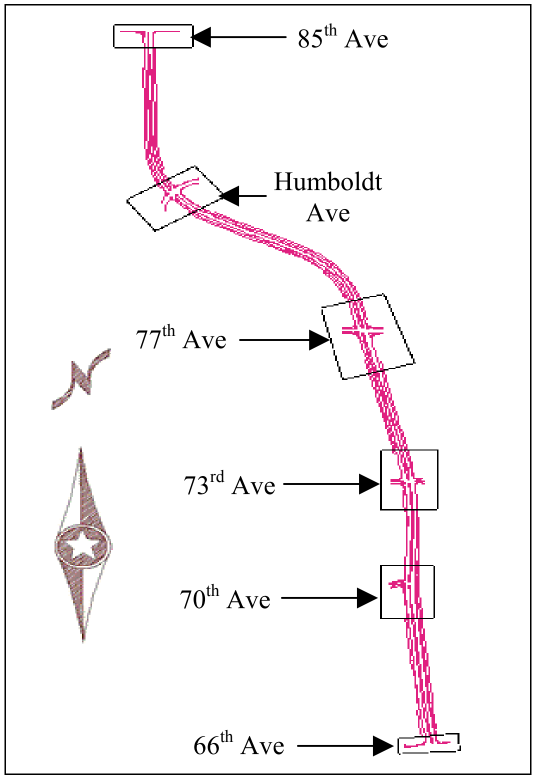


Figure 5.8 – State Highway 252 photogrammetry with intersections

The fog line transitions away from the driving lane when a turn lane begins. This turn lane data is not collected by the vision system since it is offset 3.7 meters (12 feet) to the right of the drivable lane on the far side of the turn lane and outside the field of view of the camera. Since the drivable lanes are the focus here, the data collection vehicle does not collect data in the turn lanes (Please keep in mind that for lane departure, it should only be necessary to digitize the commonly driven lanes, so warnings can be issued when unintended lane departure occurs). This results in areas where it is not possible to calculate the accuracy of the vision-based mapping system. Some of the off/on ramp-styled turn lanes have different lengths and, therefore, there are some intersections that appear relatively large. The data was collected on Highway 252 from 66th Ave to 85th Ave and there are no lane markings through the intersections.

5.4 Experimental Results

Data collected using the vision-based mapping system was compared to the static DGPS points collected for each route. All of the vision-based system's collected data was filtered and reduced using the linear regression model illustrated in Figure 5.9.

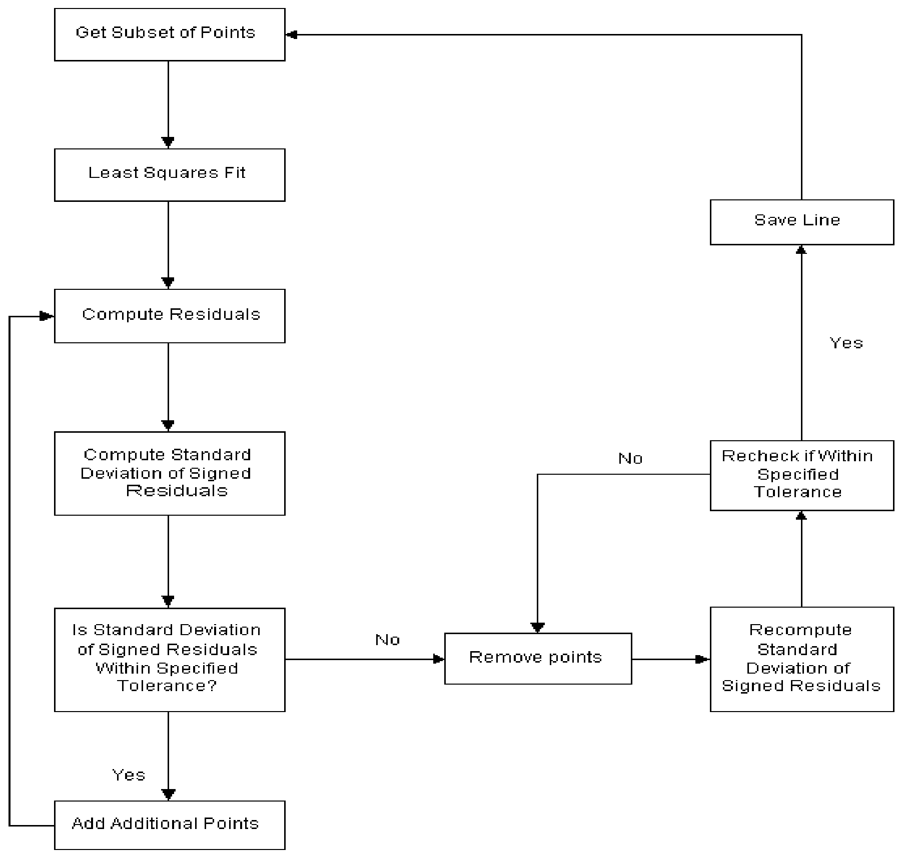


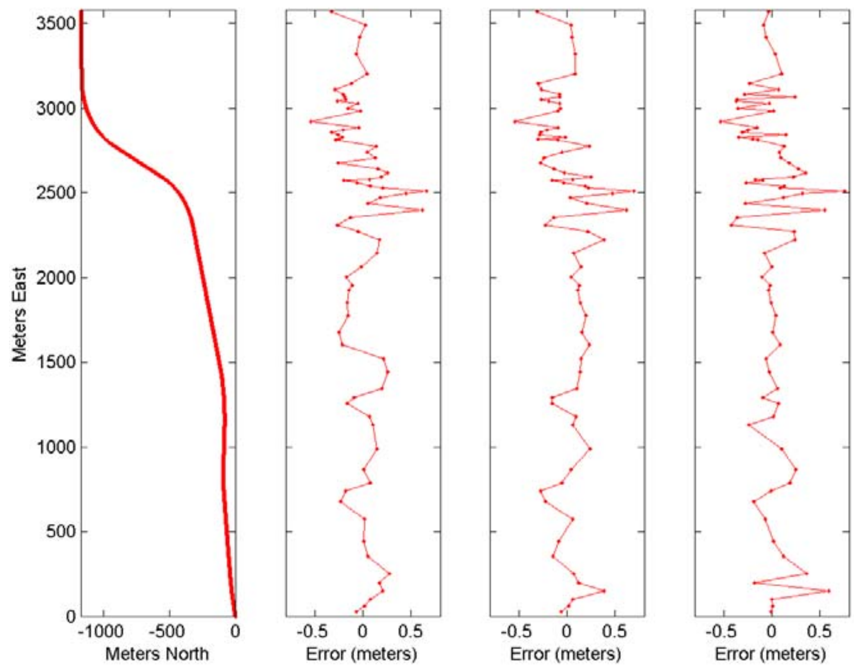
Figure 5.9 – Linear regression flow chart

Linear regression is a method for fitting a straight line through a set of data points [31][32]. A line is fit through a series of points using the Least Squares linear regression method. This method calculates the perpendicular offset, or residual, for each point from the fit line. The process begins with a query of a subset of data points in the file. A linear regression is performed on this initial set of data and the residuals for each point from the fit line are calculated. If the calculated residuals of each point are less than the specified tolerance level, an additional subset of points is added to the previous set and the regression is performed again until the residuals exceed the specified tolerance level. Once the specified tolerance level has been exceeded, the process moves backward through the list of points one at a time and recalculates the residuals. This continues until the residuals are within the specified tolerance level; the line segment is then defined and saved and the process starts anew.

For these experiments, three tolerance levels were specified: 5, 10, and 20 cm (2.0, 3.9, and 7.9 inches). By comparing the results of three different tolerance levels, it is possible to reduce the amount of data required to capture the geometry of the road and still maintain accuracy. All of the data was fit using the linear regression method described above. This results in curves consisting of many short, straight segments. It is possible to perform a regression using arcs of constant radii, but that was not used for these experiments.

The error between the vision-based mapping system results and the validation map was calculated as the perpendicular distance between the two files using the same perpendicular distance algorithm as described in Chapter 4, Section 4.1.3.

5.4.1 State Highway 252



(a) (b) (c) (d)

Figure 5.10 – (a) State Highway 252 – northbound lateral error at three tolerance levels – (b) 0.05 meter tolerance level, (c) 0.10 meter tolerance level, (d) 0.20 meter tolerance level plotted against location

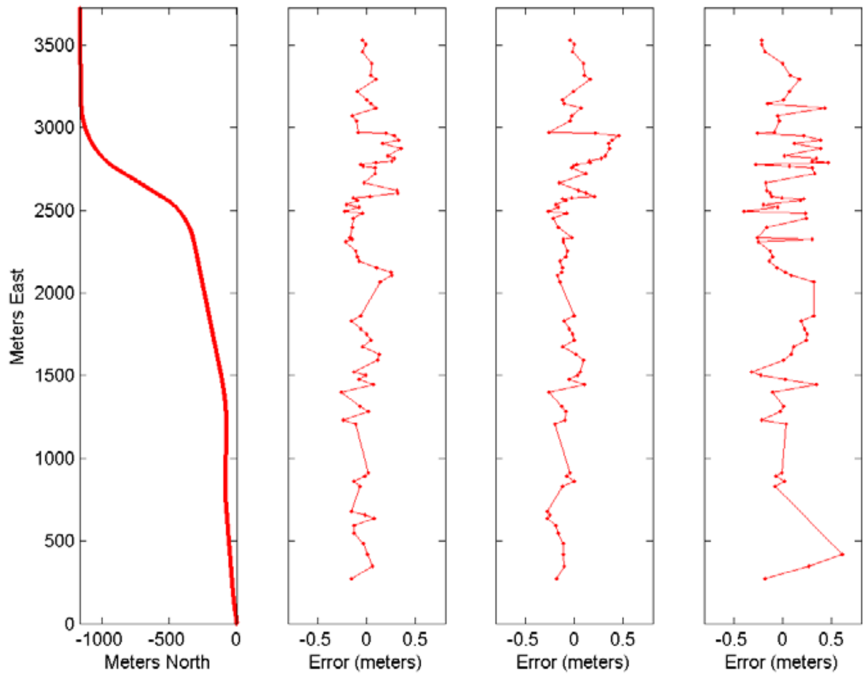


Figure 5.11 – (a) State Highway 252 – southbound lateral error at three tolerance levels – (b) 0.05 meter tolerance level, (c) 0.10 meter tolerance level, (d) 0.20 meter tolerance level plotted against location

The plotted data in Figure 5.10 and 5.11 (a) has been *zeroed-out* for route length clarity. The actual data is in the Minnesota State South Plane Coordinate System.

Figures 5.10 (a) and 5.11 (a) illustrate the geometry of State Highway 252 along with the associated error along the route for each of the specified tolerance levels of 5, 10, and 20 cm (2.0, 3.9, and 7.9 inches), which are plotted in Figures 5.10 and 5.11 (b), (c), and (d) respectively. All data shown is for the rightmost fog line in each direction.

Note that for the wider 0.20 meter tolerance level, more data is allowed by the linear regression model as part of a lane boundary and therefore results in larger errors.

Notice that all three error plots in Figure 5.11 (b), (c), and (d) do not have data for the entire route (meters east). This was due to the existence of long "on ramps" at the beginning of the test section and turn lanes at the end of the test section, as explained in Section 5.3.1, in which no fog line data exists. State Highway 252 was used as one data set because it was an example of a road with many intersections and turn lanes that can affect the mapping process and the accuracy.

For both the Northbound and Southbound routes, the data collected using the vision-based system was reduced using the linear regression model explained in Section 5.4. It is possible to see that the greatest error occurs near the curved sections of the road. Since the data is fit using a linear regression model, this was expected.

Table 5.1 shows statistics for the data collection vehicle's speed and the vision-based data collection rate in frames per second. State Highway 252 has signaled controlled intersections, which require the vehicle to stop occasionally and cause the minimum speed to become 0.00 kph (0.00 mph).

Table 5.1 – Highway 252 – Vehicle speed (kph) during collection

Speed	Maximum Speed (kph)	Minimum Speed (kph)	Mean Speed (kph)	Frames per Second
Northbound	76.51	0.00	66.45	15.71
Southbound	77.46	0.00	61.67	16.06

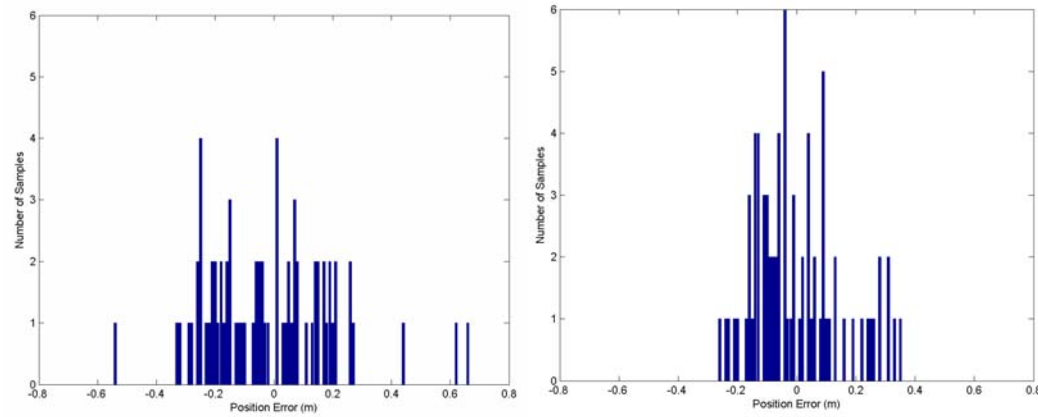
Since the raw, collected data was filtered using linear regression, this resulted in a data file with the same geometry, but with a reduced density of points. Table 5.2 shows length of the route, the number of points collected with the vision-based system, and the resulting number of points after performing linear regression at each specified tolerance level: 5, 10, and 20 cm (2.0, 3.9, and 7.9 inches).

Table 5.2 – Highway 252 – Number of data points collected and database results

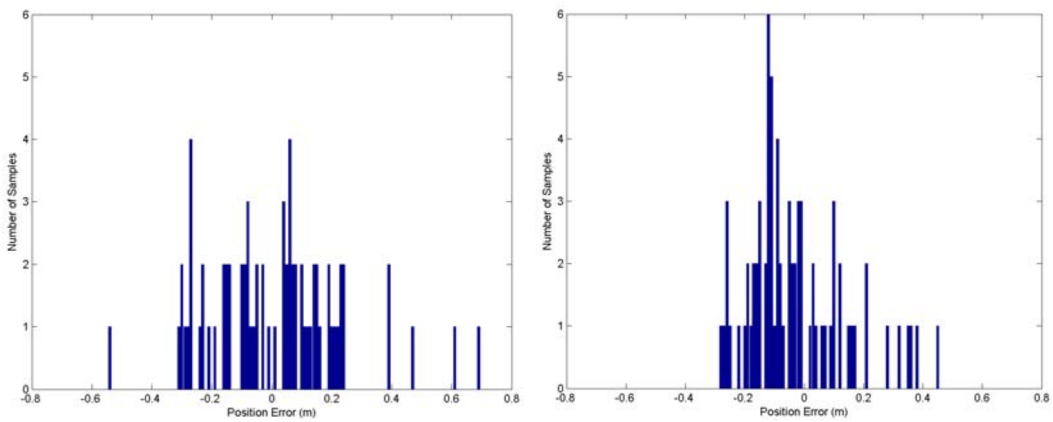
Direction	Length of Route km / miles	Collected Number of Points	Number of Points, 5 cm Tolerance level	Number of Points, 10 cm Tolerance level	Number of Points, 20 cm Tolerance level
Northbound	4.0 / 2.5	1886	70	49	32
Southbound	4.0 / 2.5	1713	73	46	33

It is important to note that the data was reduced for the 5 cm tolerance level 27:1 and 23:1 northbound and southbound respectively. By doubling the tolerance level to 10 cm, the reduction is 38:1 northbound and 37:1 southbound and for quadrupling the tolerance level to 20 cm, the data reduces to 59:1 and 52:1 for north and southbound directions respectively.

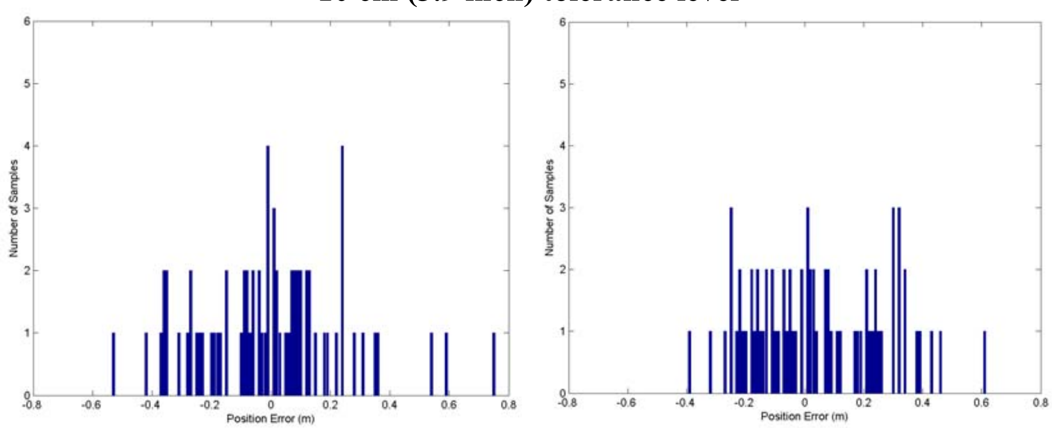
Figures 5.12 show histograms (all histogram bins are one centimeter wide.) of the position errors for State Highway 252 for Northbound and Southbound. Tables 5.2 and 5.3 lists the error statistics for each of the three specified tolerance levels: 5, 10, 20 cm (2.0, 3.9, and 7.9 inches).



5 cm (2.0 inch) tolerance level



10 cm (3.9 inch) tolerance level



20 cm (7.9 inch) tolerance level

Figure 5.12 – State Highway 252 – position error histogram – northbound left column, southbound right column

Table 5.3 – Highway 252 northbound – errors

Specified Tolerance level (cm)	Max Error Right of Lane Marking (cm)	Max Error Left of Lane Marking (cm)	Mean Error (cm)	Standard Deviation (cm)
5	65.92	-53.75	1.99	21.36
10	69.03	-53.65	0.84	21.97
20	75.25	-53.31	0.20	23.48

Table 5.3 lists the error statistics for the northbound lane on State Highway 252. Positive error denotes the data is to the right of the lane marking center and negative error is to the left of the lane marking. The mean error is very small for each of the three tolerance levels and the standard deviation is slightly more than 20 cm (7.9 inches). The right column of histograms from Figure 5.12 shows that nearly all of the data (91.8 %, 89.0 %, and 80.8 % for 5, 10, and 20 cm tolerance levels respectively) is within 30.5 cm (12 inches) of the center of the lane marking.

Table 5.4 – Highway 252 southbound – errors

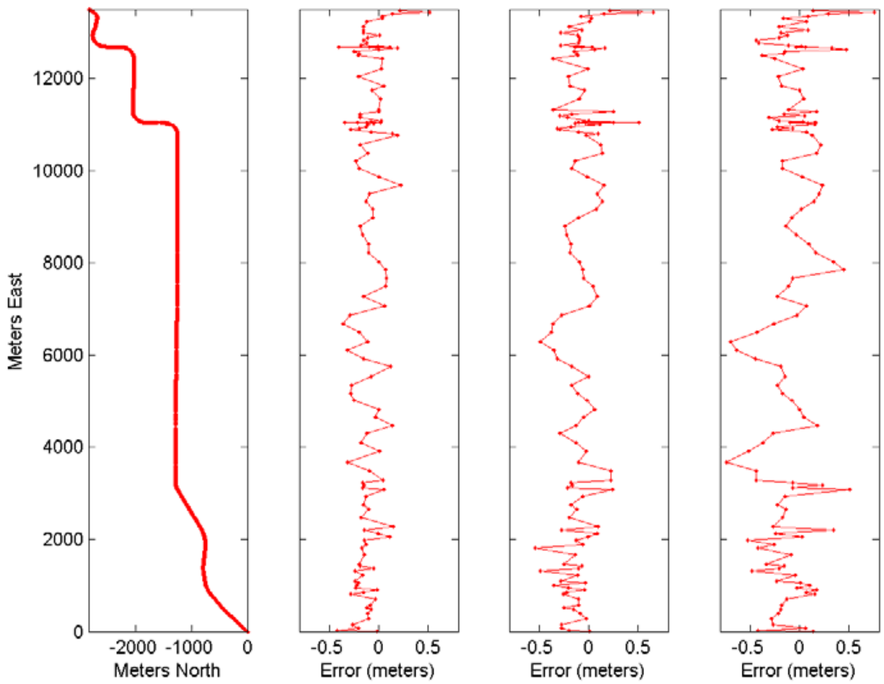
Specified Tolerance level (cm)	Max Error Right of Lane Marking (cm)	Max Error Left of Lane Marking (cm)	Mean Error (cm)	Standard Deviation (cm)
5	35.35	-25.64	-0.09	14.61
10	45.05	-27.69	-2.93	15.94
20	61.17	-38.95	-4.05	21.67

The error statistics for the southbound lane of State Highway 252 are shown in Table 5.4. The mean error is again small for each of the three tolerance levels but with a smaller standard deviation. Observing the position error histograms in the right column of Figure 5.12, the majority of the data (94.9 %, 93.7 %, and 83.6 % for the 5, 10, and 20 cm tolerance levels respectively) is within 30.5 cm (12 inches).

Reducing the amount of data using linear regression and computing the perpendicular distance of the data from the validation map can increase the errors by not accurately capturing the curved geometry. However, the majority of error for State Highway 252 is less than 30.5 cm (12 inches) with a significant amount (Northbound – 64.4 %, 64.4 %, and 63.0 % and Southbound – 81.0 %, 81.0 %, and 57.5 % for the 5, 10, and 20 cm tolerance levels respectively) within 20 cm (7.9 inches) for the center of the lane marking.

The number of data points is also important to look at in the context of the error. Relaxing the tolerance level from 10 cm (3.9 inches) to 20 cm (7.9 inches) reduces the number of data points (Table 5.2), but can result in greater positional error and a larger standard deviation (Tables 5.3 and 5.4).

5.4.2 McLeod County 2



(a) **(b)** **(c)** **(d)**

Figure 5.13 – McLeod County 2 – northbound lateral error at three tolerance levels – (b) 0.05 meter tolerance level, (c) 0.10 meter tolerance level, (d) 0.20 meter tolerance level plotted against location

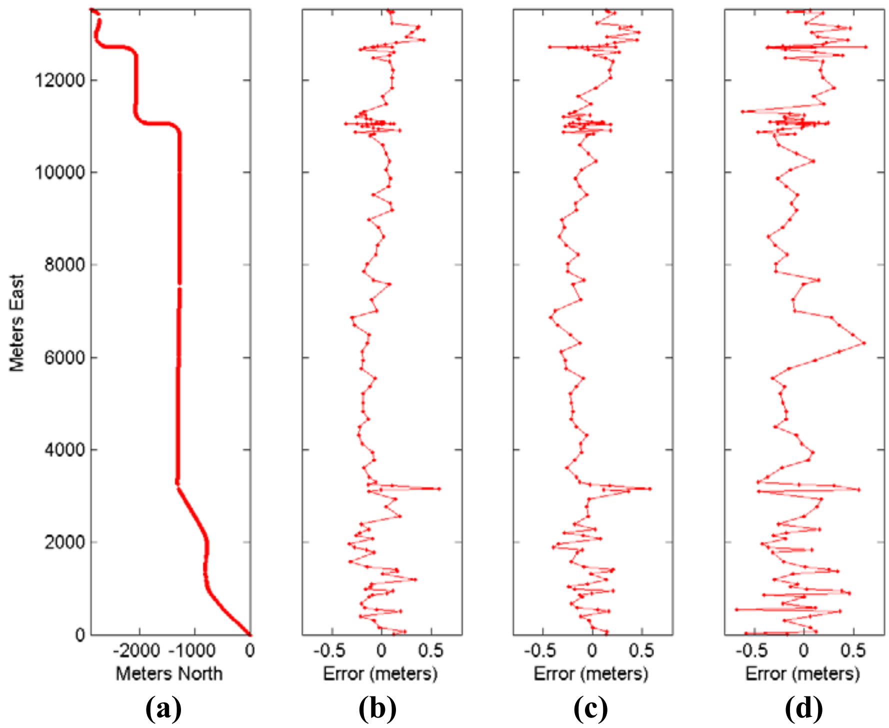


Figure 5.14 – McLeod County 2 – southbound lateral error at three tolerance levels – (b) 0.05 meter tolerance level, (c) 0.10 meter tolerance level, (d) 0.20 meter tolerance level plotted against location

The plotted data in Figure 5.13 and 5.14 (a) has been *zeroed-out* for route length clarity. The actual data is in the Minnesota State South Plane Coordinate System.

Figure 5.13 and 5.14 (a) shows the geometry of McLeod County 2 northbound and southbound routes respectively. The error along the northbound and southbound routes for each of the three linear regression tolerance levels, 5, 10, and 20 cm (2.0, 3.9, and 7.9 inches) are shown in Figures 5.13 (northbound) and 5.14 (southbound) (b), (c), and (d). Again all data shown is for the rightmost fog line in each direction.

The raw data from the vision-based system was fit using the linear regression model described in Section 5.4 and the result was compared to fiduciary points for the McLeod County 2 route. The error shown in Figures 5.13 and 5.14, plots (b), (c), and (d), show that there were large errors when the road curved. Since McLeod County 2 has very sharp curves, which can lead to larger errors, it is an ideal test route for the vision-based data collection system. However, the error in the middle of the longest straight section also has a large error spike. Since the data was fit using a linear regression model and the error was calculated using a perpendicular offset method, large errors along the curves are expected. Along the straight segment the error may be due to a false positive data point.

The statistics for the data collection vehicles's speed and the data collection rate is shown in Table 5.5. Since McLeod County 2 does not have any signal-controlled intersections, the vehicle does not stop and results in a positive minimum speed. The reduced speed is due to sharp curvature along the road.

Table 5.5 – McLeod County 2 – vehicle speed (mph) during collection

Speed	Maximum Speed (kph)	Minimum Speed (kph)	Mean Speed (kph)	Frames per Second
Northbound	60.40	24.64	54.09	10.46
Southbound	67.54	10.14	53.09	10.77

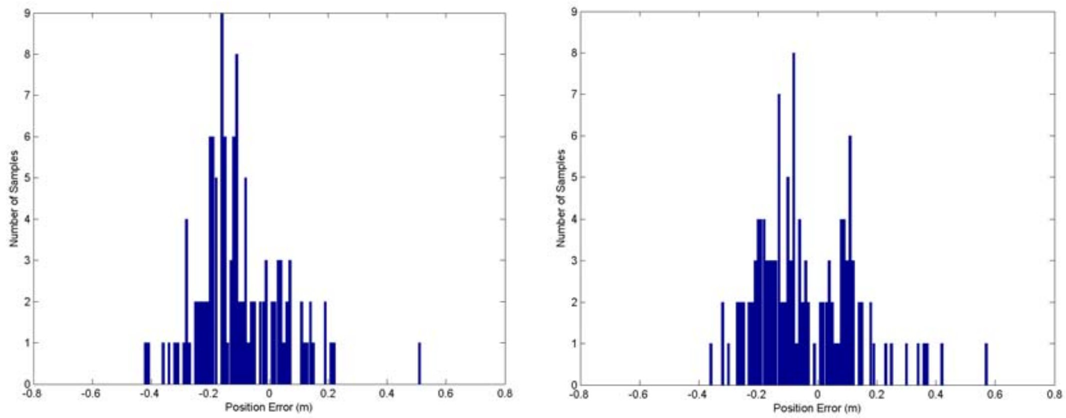
The density of the collected points for McLeod County 2 was reduced using the same linear regression method and tolerance levels (5, 10, and 20 cm (2.0, 3.9, and 7.9 inches)) described earlier. The length of the route and the number of data points collected are shown in Table 5.6. Also included in Table 5.6 is the number of remaining points after fitting the raw data at 5, 10, and 20 cm (2.0, 3.9, 7.9 inch) tolerance levels.

Table 5.6 – McLeod County 2 – number of data points collected and database results

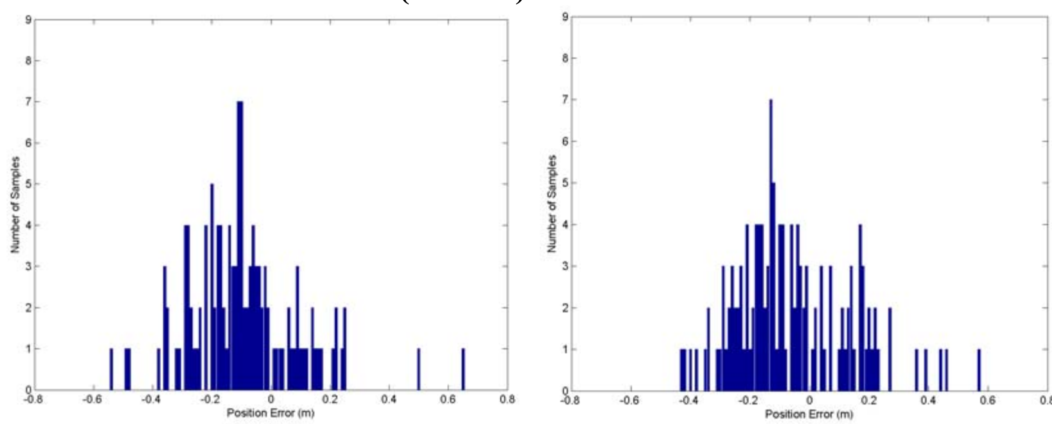
Direction	Length of Route km / miles	Collected Number of Points	Number of Points, 5 cm Tolerance Level	Number of Points, 10 cm Tolerance Level	Number of Points, 20 cm Tolerance Level
Northbound	15.3 / 9.4	7262	230	138	89
Southbound	15.3 / 9.4	7703	233	133	90

Data reduction is significant for McLeod County 2 due to the long straight sections of the road. The data was reduced for the 5 cm tolerance level 32:1 northbound and 33:1 southbound. Using a 10 cm tolerance level, the reduction is 53:1 and 58:1 northbound and southbound respectively and for the tolerance level of 20 cm, the data reduces to 82:1 northbound and 86:1 and southbound directions.

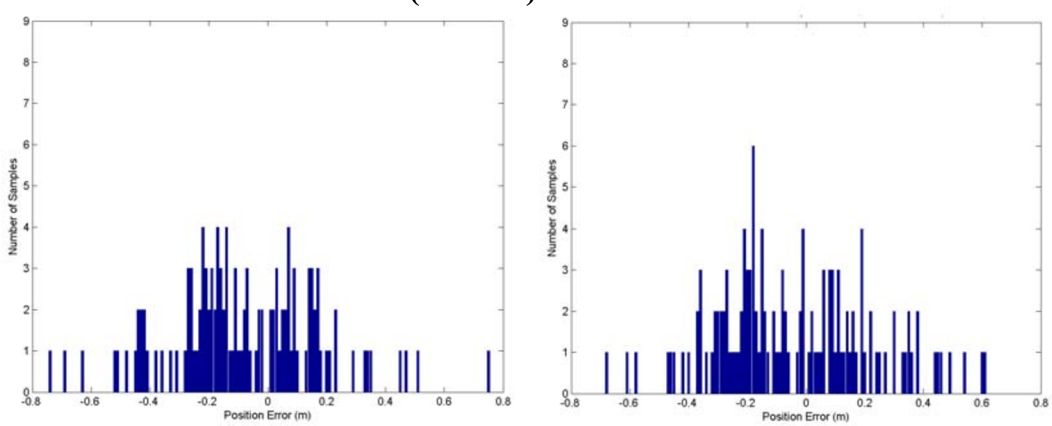
The position error histograms (all histogram bins are one centimeter wide) for northbound and southbound McLeod County 2 at each tolerance level are shown in Figures 5.15. Tables 5.7 and 5.8 list the error statistics.



5 cm (2.0 inch) tolerance level



10 cm (3.9 inch) tolerance level



20 cm (7.9 inch) tolerance level

Figure 5.15 – McLeod County 2 – position error histogram – northbound left column, southbound right column

Table 5.7 – McLeod County 2 northbound – errors

Specified Tolerance level (cm)	Max Error Right of Lane Marking (cm)	Max Error Left of Lane Marking (cm)	Mean Error (cm)	Standard Deviation (cm)
5	51.23	-42.13	-9.58	14.14
10	64.68	-54.06	-9.45	17.96
20	75.13	-73.68	-8.12	24.62

The error statistics for the northbound lane of McLeod County 2 are shown in Table 5.7. The mean error is nearly 10.0 cm (3.9 inches), but the standard deviation is under 25.0 cm (9.8 inches). Again, a positive error is to the right of the lane marking center and a negative error is to the left of the lane marking center. Most of the data (94.5 %, 89.7 %, and 79.5 % for the 5, 10, and 20 cm tolerance levels respectively), as shown in Figures 5.18 – 5.20, is again within 30.5 cm (12 inches) of the validation map.

Table 5.8 – McLeod County 2 southbound – errors

Specified Tolerance level (cm)	Max Error Right of Lane Marking (cm)	Max Error Left of Lane Marking (cm)	Mean Error (cm)	Standard Deviation (cm)
5	57.47	-36.16	-4.18	16.30
10	57.49	-42.63	-5.91	19.14
20	61.40	-67.78	-4.09	25.81

Table 5.8 displays the error statistics for the southbound lane of McLeod County 2. The standard deviation for the 5 and 10 cm (2.0 and 3.9 inches) tolerance levels are under 20 cm (7.9 inches) and the 20 cm (7.9 inches) tolerance level is below 30.5 cm (12 inches). The mean error for the three tolerance levels is small and within the accuracy of the DGPS unit. Examining the position error histograms for the southbound lane (Figures 5.21-5.23), the majority of the data points (93.9 %, 89.4 %, and 75.6 % for the 5, 10, and 20 cm tolerance levels respectively) are within 30.5 cm (12 inches).

Most of McLeod County 2's geometry is straight, but there are some very sharp curves (four 90° curves, one less than 90° curve). Through the combination of linear regression and using the perpendicular offsets of the data points from the validation map, the error may appear larger on the curved sections than in reality. The majority of the data is again less than 30.5 cm (12 inches) with a significant amount (Northbound – 78.7 %, 69.0 %, and 59.8 % and Southbound – 78.8 %, 66.7 %, and 56.5 % for the 5, 10, and 20 cm tolerance levels respectively) within 20 cm (7.9 inches) from the center of the lane marking.

Table 5.6 shows the significant reduction in the density of data points when using the linear regression method to reduce the raw data. Again, by relaxing the tolerance level to 20 cm (7.9 inches), the standard deviation increases. By setting the linear regression tolerance level to 10 cm or less, it is possible to create a map that is accurate to 20 cm (7.9 inches) when using the vision-based data collection system.

It is important to understand that computer vision systems may give conflicting results for the same image depending on many circumstances (light index, reflection, etc.). The size of one pixel is known to be 0.45 cm (0.18 inches) square and this results in a 10.2 cm (4 inch) wide lane marking measuring approximately 25 pixels wide in the image. False positives can occur, as explained in Chapter 3, and those can offset the raw data by as much as the field of view of the camera, 25.5 inches.

5.5 Quality Assurance

While it may not be possible to always check the results against photogrammetry or a very accurate map, such as the fiduciary point method described in this document, it is possible to perform an on-site check immediately after the data is collected by using the HUD [14][15][16] which is shown in Figure 1.1. By creating a road geospatial database from the collected data, it is possible to drive the newly digitized route and use the HUD to determine whether or not the geospatial database is lined up and correct.

5.6 Alternative Data Collection Comparison

Previously, the IV Lab created high accuracy digital maps by collecting data for each lane by making multiple passes. This is a time-consuming collection task that produces multiple files for a single lane. By using the vision-based system, multiple passes and data collection in each lane is not necessary. This reduces the number of files requiring processing as well as the time spent collecting data on each route.

As previously mentioned, each of the routes, State Highway 252 and McLeod County 2, had been digitized for past projects. This enabled a comparison between the amount of data needed and time required for each method. Table 5.7 shows the raw numbers using each method on each route.

Table 5.7 – Data collection comparison statistics

Route	Method	Time Required for Collection	Number of Files Saved	Amount of Data Stored
Highway 252	Multiple Runs	107.90 min	18	5.49 MB
	Vision System	16.32 min	4	438 KB
County 2	Multiple Runs	86.33 min	8	4.20 MB
	Vision System	34.08 min	2	1.78 MB

State Highway 252 is a 4.0-km (2.5-mile), multi-lane, divided highway with a maximum of three lanes in each direction, totaling six lanes. By using the Multiple Run method, each lane was driven a minimum of three times. This resulted in eighteen files requiring 107.90 minutes to collect the data. Consequently, the amount of storage space required increases due to the number of files containing (roughly) the same amount of data per file. While this increase of data is relatively negligible, it can add up over time for routes that are longer and similarly constructed.

The Vision System method, based on the definition described in Chapter 2, allows for fewer passes over the road, one pass per fog line. This results in a shorter time collecting data and requires less storage space. If the Vision System method is used, it is possible to collect the same amount of information 1.5 hours faster and using 5 MB less of storage space than using the Multiple Run method.

McLeod County 2 is a 15.1 km (9.4-mile), two-lane, non-divided highway. In this case, there is only one lane in each direction. However, data was collected for three runs using the *Multiple Runs* method, which required 86.33 minutes to complete the data collection. Due to the longer length and the sharper turns, which required slower speeds, the amount of data that is stored is larger than for Highway 252. The amount of storage using the Multiple Run method is 2.4 times as much as the *Vision System* and takes 2.5 times longer to collect.

Chapter 6
Costs

A high-accuracy geospatial database representing lane boundaries for all national rural roads and highways would support numerous safety applications, and lane departure warnings in particular. National deployment of these systems would produce substantial benefits, both in terms of lives saved and in increased mobility. The technologies enabled by this geospatial database could potentially save hundreds of lives annually in the US as well as improve mobility for those vehicle operators required to drive under difficult environmental conditions.

Two unanswered questions have delayed the deployment of a national map:

1. The cost to create the initial geospatial database
2. The cost to maintain the geospatial database once it is created.

To address these questions, a model to estimate the cost to develop a geospatial database containing lane boundary information is presented. The model presented is based on data collection efforts documented in previous chapters and on weather, road, and DGPS correction conditions found in Minnesota. Two important assumptions guide the development of this model:

- The road model contains only information regarding the location of lane boundaries. Information regarding guardrails, signage, mailboxes, and intersection geometry are not contained within the proposed database. Limiting the database to this data set enables a significant number of applications, in particular lane departure warning and rural snowplowing, and facilitates a relatively rapid deployment of the database. Should applications requiring additional information be developed, the lane boundary database can be augmented to included additional data.
- Weather effects, including rain, snow, and ice allows data collection to occur only 30 weeks of the year. Productivity in more southern states is likely higher, which would result in a lower overall cost to create the map.

A third assumption affects the cost model, but not to the extent that the two assumptions above do. Minnesota is working to provide VRS-based DGPS correction coverage throughout the state. This coverage greatly expedites the creation of geospatial databases because corrections are readily available. In Minnesota, as of April 2005, approximately thirty percent of the state was covered by VRS. In locations where DGPS corrections are unavailable, two options are available:

- Establishment of a local GPS base station, which combined with a wireless communication channel, provides Real Time Kinematic (RTK) DGPS capability when in relatively close proximity to the base station.
- Collection of raw satellite observable data to be subsequently post-processed using reference station data.

Both options add cost to the data collection process. To support RTK corrections from a local base station, the base station GPS antenna location must be accurately located. This can be done either by placing the base station antenna on a High Accuracy Reference Network (HARN) survey marker or by collecting static location data, and subsequently post-processing to determine an accurate position. HARN survey marker density is quite variable, so the presence of a marker suitably located to support map data collection is not guaranteed. Collecting base station location data and subsequent post-processing requires 4 hours of data collection, and a 12 hour delay before that position can be post-processed. On average, this RTK approach would likely decrease the amount of lane miles, which could be mapped in any given year by one-half.

The second option involves the collection of raw satellite observable information on the mapping vehicle while image data is captured and processed. Once raw observable data is collected, it can be post-processed using data collected from a GPS reference network and post-processing software which is commercially available. (One source of post-processing software is Waypoint Consulting, Inc; see http://www.waypoint.com/.) Assuming that a source of reference GPS base station data is available, this approach would have an insignificant impact on the amount of lane miles that could be mapped in any given year. The primary impact on the mapping process would be on the capital cost of the software needed to execute the post-processing task.

With these caveats, costs to create a road boundary geospatial database for Minnesota, and subsequently extrapolated to the entire US is provided below.

6.1 Equipment

6.1.1 DGPS

The primary (and most costly) piece of equipment is the DGPS unit. A Trimble MS750 DGPS unit, used for the experiments conducted in this paper, can cost up to $15,000 (DOT price for the MS750 system including receiver, antenna, and cable set). The MS750 has been used satisfactorily by the IV Lab for six years and has verified and documented its accuracy. The MS750 unit can achieve a mean error of about 2-5 cm statically at $\pm 1\sigma$ and 5-8 cm dynamically at $\pm 1\sigma$, while using an RTK or VRS correction [28]. This system requires a differential correction method and some states, as well as the FHWA, are looking into methods to achieve a broadly available correction system. Currently Minnesota is leading statewide deployment of VRS on a national basis, with other states such as North Carolina and Ohio also operating VRS systems.

The FHWA is working on a nationwide correction system, the High Accuracy Nationwide DGPS (HA-NDGPS) [33]. This method compresses and modulates a GPS signal and uses the existing NDGPS (1-3 meter (3.3-9.8 feet) accuracy) infrastructure in order to broadcast the corrections. The HA-NDGPS signal uses a low frequency broadcast technique that has been used by aviation and maritime radio navigation systems. The correction signal, which has carrier phase resolution, is compressed to best utilize available broadcast frequency bandwidth. Use of this HA-NDGPS correction requires specially equipped GPS units which can decompress the HA-NDGPS signal. The static accuracy of a HA-NDGPS receiver is currently within 10 cm (3.9 inches).

VRS is most likely the preferred choice for the near future differential corrections because there are fewer reference stations required (one every 50 km (31 miles) versus RTK's requirement of one approximately every 24 km (15 miles)). Given a fixed number of DGPS base station receivers, the coverage area of a networked solution is typically four times greater then the area provided by non-networked base stations. At this time, the IV Lab does not pay a fee to Mn/DOT (Minnesota's VRS provider and maintainer) to use Mn/DOT's VRS service. It is reasonable to assume that there would be a fee for a user if the data were used for commercial purposes.

If the proper telecommunication infrastructure is in place, the correction signal can be broadcast and received using existing, widely available, wireless services. This circumvents the need to broadcast corrections on a dedicated, FCC-licensed radio frequency. The IV Lab has used a data-capable CDMA cellular phone in order to receive DGPS corrections, both from a discrete base station and from the Mn/DOT VRS server. Depending on the wireless plan purchased, the phone can cost anywhere from $0-250.00 with an accompanying wireless plan. Table 6.1 lists the required items and their current price, assuming a VRS-based GPS correction.

Table 6.1 – DGPS cost

Item	Cost (US Dollars/Unit)
Capital Costs	
DGPS - Trimble MS750	15,000.00
Cellular Phone	250.00
Annual Operational Costs	
Cell plan (Unlimited Data) $80/month (x 12 month/year)	960.00
Total	**16,210.00**

6.1.2 Computer

The computer used in this system can either be a desktop, a laptop, or a rugged laptop such as the Panasonic Toughbook CF-18. The minimum requirements are:

- a 2 GHz processor,
- USB 2.0,
- and two RS-232 serial ports (one for DGPS, one for VRS correction).

While these requirements are readily available on a basic desktop computer, most laptops only have a single RS-232 serial port. An additional piece of hardware, an RS-232 Serial PCMCIA card can be employed to expand the number of serial ports. Because of the difficult data collection environment, a Toughbook computer is recommended due to its rugged design. Table 6.2 lists the cost for a Panasonic Toughbook and a RS-232 Serial PCMCIA card.

Table 6.2 – Computer capital costs

Item	Capital Cost (US Dollars/Unit)
Panasonic Toughbook CF-18	3,300.00
Qautech 2 port RS-232 PCMCIA	200.00
Total	**3,500.00**

6.1.3 Camera, Illumination, Hardware

The required hardware associated with the camera and the illumination source is listed in Table 6.3. For the experiments described in this document, the system consists of an Orange Micro iBot camera with USB extension cable and an illumination source consisting of a 300-Watt commercial grade quartz floodlight with an opal diffuser and the associated hardware. The equipment is attached to a camera mount that was custom designed specifically for the SAFEPLOW. The University of Minnesota Mechanical Engineering Machine Shop built the camera mount to IV Lab specifications. A power inverter is both used to power the illumination source and as an AC power source for the computer.

Table 6.3 – Camera, illumination source, and mounting hardware

Item	Capital Cost (US Dollars/Unit)
Camera - Orange Micro iBot	80.00
USB Extension Cable - 10 ft	25.00
Light - 300 W with Diffuser and Hardware	76.00
Camera Mount	546.00
Inverter - Radio Shack 300 W	100.00
Total	**827.00**

The final cost for all of the equipment is $20,537.00 based on the selected Toughbook computer.

6.2 Vehicle Costs

Given the relatively low technical demands placed on the data collection vehicle, it is unlikely that a county or state agency will purchase and dedicate a vehicle to the data collection process. Therefore, it is assumed that parties interested will allocate a vehicle that can be used for data collection. However, the maintenance and operational costs of a vehicle are important and are considered here. In order to evaluate the maintenance and operational costs, the following assumptions are made:

- 231.7 km (144 miles) lane miles of good data collected per day (based on 4.5 hours of data collection at an average speed of 64.4 kph (40 mph) of which 80% of the collected data is good)

- 218.9 km (136 miles) per day of additional driving not used for collecting data (160.9 km (100 miles) to and from route, gas station, etc., 57.9 km (36 miles) of data collected but not useable)
- Data collected 3 days per week, data is processed and formatted 2 days per week
- Data collected 30 weeks per year (only 30 weeks are assumed due to times when collection is not possible due to inclement weather (rain or snow) in Minnesota)
- Mileage and maintenance cost at $0.47 per km ($0.76 per mile) – Mn/DOT pick-up truck rate (not including vehicle insurance)

This amounts to a total of 20,857.1 km (12,960 miles) collected per year with an additional 19,698.4 km (12,240 miles) that are driven but for which data is not collected, yielding a total of 40,555.5 km (25,200 miles) per year. At $0.47 per km ($0.76 per mile), the approximate cost is $19,152.00 per year for refueling costs and vehicle maintenance.

6.3 Labor

The data collection system uses a GUI to facilitate collection and appropriate filenames as explained in Chapter 4. For the method described herein, the data collection typically consists of starting and stopping the system with an occasional change in filename information. The driver of the vehicle can easily accomplish this. While it is reasonable to assume that a second operator could monitor the system and assist with data collection, it is possible to collect the basic geometry with a single operator. The assumed salary plus benefits for a full time employee (8 hours per day, 5 days per week, 52 weeks per year) was set at $53,000. Because the driver would be collecting data for mapping purposes only 30 weeks of the year, $31,000 of the $53,000 salary (benefits included) factors into the cost model.

Table 6.4 shows the capital and operational costs for data collection explained thus far.

Table 6.4 – Data collection costs

Data Collection	Cost (US dollars)
Capital Cost	
Equipment	19,577.00
Annual Operational Cost	
Equipment (Cell phone service)	960.00
Vehicle	19,152.00
Operator	31,000.00
Total	70,689.00

6.4 Quality Assurance

The quality of the collected data must be checked, and improved where found deficient. In order to accomplish this, additional personnel and equipment is required. Because the data collection must occur during the night, the data can be checked for accuracy in the daytime. This allows the vehicle used for data collection to be used for the quality assurance.

As explained in Chapter 5, Section 5.5, the use of a VES system, which includes a HUD (as shown in Figure 1.1), can be used to compare the physical road to the newly created geospatial database for that same road. This requires additional hardware consisting of a combiner, projector, and a computer that can run the software required to project the geometry of the lane boundaries in the geospatial database. This additional hardware is approximately $7,000.

Because the route must be driven again for quality assurance, there are additional miles that must be factored into the cost. The amount of miles driven during quality assurance is limited by the total amount of miles driven by the data collection vehicle. These numbers are summarized below:

- 289.7 km (180 miles) lane miles driven per day (based on 4.5 hours of data collection at an average speed of 64.4 kph (40 mph))
- 160.9 km (100 miles) per day of additional driving to and from route, gas station, etc.
- Quality Assurance performed 3 days per week
- Quality Assurance performed 30 weeks per year (only 30 weeks are assumed due to times when quality assurance is not possible due to inclement weather (rain or snow) in Minnesota)
- Mileage and maintenance cost at $0.47 per km ($0.76 per mile) – Mn/DOT pick-up truck rate (not including vehicle insurance)

This amounts to a total of 26,071.4 km (25,200 miles) driven for quality assurance per year at a cost of $19,152.00 per year for refueling costs and vehicle maintenance.

An operator is also required to drive the vehicle and to check the quality of the data collected. An additional operator salary plus benefits for quality assurance was assumed to be $63,000 (a higher pay scale for this employee). Again this operator only performs the quality assurance task for 30 weeks out of the year and therefore only $37,000 (salary and benefits) is applied to the cost of mapping.

The costs associated with the quality assurance function are shown below in Table 6.5.

Table 6.5 –Quality assurance costs

Quality Assurance	Cost (US dollars)
Capital Cost	
VES System	7,000.00
Annual Operational Cost	
Vehicle	19,152.00
Operator	37,000.00
Total	63,152.00

6.5 Total Cost to Map

Table 6.6 below indicates the initial per mile cost to create a geospatial database in Minnesota under the assumption that the capital costs are covered in the first year. Clearly, second year per mile costs will be lower regardless whether capital costs are amortized or completely absorbed in the initial year costs.

Table 6.6 – Minnesota calculated cost per mile (first year cost: operating and capital cost)

Expense	Cost (US Dollars)
Capital Cost	
Equipment (Data Collection and Quality Assurance)	26,577.00
Annual Operational Cost	
Equipment (Data Collection and Quality Assurance)	960.00
Vehicle (Data Collection + Quality Assurance)	38,304.00
Operator (1 each for Data Collection and Quality Assurance)	68,000.00
Total Annual Operating Cost	107,264.00
Total Expenses (Capital + Operational)	**133,841.00**
Total Equivalent Lane Miles Mapped per Year	12,960
Cost To Map (per Mile per Vehicle per Year)	**10.33**

According to the FHWA's "Public Road Length in the United States" data (See Appendix A, Table A.1) for 2003, Minnesota has 186,175.4 total rural road kilometers (115,684 miles). In order to map every rural road in Minnesota, in both directions, data needs to be collected for at least 372,350.7 lane km (231,368 miles) (i.e. 186,175 km multiplied by two directions). Many roads, including interstates, are divided by some means and, therefore, require more than a single pass per direction. Since more than a single pass may be necessary, the number of divided and undivided roads is required. According to the FHWA (See Appendix A, Table A.2), approximately 91% of rural roads are undivided. As explained earlier, an undivided road requires one pass per direction and a divided road requires 2 passes per direction. Taking this into account and approximating the number of miles that are divided and undivided, a multiplier of 2.18 is assumed to be satisfactory and results in the 405862.1 total rural kilometers (252,191 miles) of road in Minnesota that require data collection. The multiplier, 2.18, is found by adding 2 passes multiplied by 91% and 4 passes multiplied by 9%. Table 6.7 shows the required cost and the time frame required to complete data collection for the state of Minnesota.

Table 6.7 – Total cost and time frame required for Minnesota (dollars rounded to nearest 500)

Number of Collection Vehicles	Rural Road Miles Mapped	Equivalent Lane Miles Mapped	Time Frame (Years)	Total Capital Cost (US Dollars)	Total Operating Cost (US Dollars)	Total Cost per Year (US Dollars)	Cost per Lane Mile (US Dollars)
1	115,684	252,191	19.5	26,500	2,092,000	109,000	8.40
4	115,684	252,191	4.9	106,000	2,102,000	451,000	8.76

The total operating cost is found by taking $107,264 (Total Operating Cost from Table 6.6) and multiplying by the number of required vehicles and the number of years required to complete mapping. By summing the Total Capital Cost and Total Operating Cost and dividing by the number of years required to complete mapping the rural road system of the specified area, the Total Cost per Year was determined.

For illustrative purposes, statistics for Minnesota (from Table 6.6) and the United States are shown in Table 6.8 along with the cost of mapping per calendar year.

Table 6.8 – Total cost and time frame required for Minnesota and the United States (dollars rounded to nearest 500)

Area - Number of Collection Vehicles	Rural Road Miles Mapped	Equivalent Lane Miles Mapped	Time Frame (Years)	Total Capital Cost (US Dollars)	Total Operating Cost (US Dollars)	Total Cost per Year (US Dollars)	Cost per Lane Mile (US Dollars)
Minnesota - 1	115,684	252,191	19.5	26,500	2,092,000	109,000	8.40
Minnesota - 4	115,684	252,191	4.9	106,000	2,102,000	451,000	8.76
U.S. - 50	3,036,293	6,619,119	10.2	1,325,000	54,705,000	5,493,000	8.46
U.S. - 100	3,036,293	6,619,119	5.1	2,650,000	54,705,000	11,246,000	8.67
U.S. - 200	3,036,293	6,619,119	2.6	5,300,000	55,777,000	23,491,000	9.23

Table 6.8 shows that with additional vehicles, it is possible to collect highly accurate data for a geospatial database for the entire rural road system in the United States within three years. While this method requires the use of 200 vehicles, on average, there are four vehicles per state. However, with the increase in the number of vehicles, the equipment and operating costs to map the entire rural road system in the U.S. is approximately 61 million dollars.

The data computed here is for a stand-alone mapping group and does not account for DOTs or other groups using vehicles and personnel already in service as a mapping team. Training a team to collect and process data is minimal and can be delegated to those people already doing field work for state DOTs or counties.

Chapter 7
Conclusions

This report outlines the concept of using a vision-based data collection system to create a high accuracy geospatial database. The proposed geospatial database is accurate enough to determine where each lane boundary is and when a lane departure may occur. Due to the many fatalities that occur on rural roads because of vehicular lane departures, this accurate lane marking database can help reduce those fatalities. Note in the interest of cost and time reductions, details regarding intersections, turn lanes, etc. were not included, but these can be added later as needed.

Using road design standards and some assumptions, it is possible to define the road so that data collection can occur efficiently. Real-time data collection of the outermost lane markings, defined as the fog lines, using a camera and DGPS antenna aligned coaxially, can capture enough information to accurately locate the lane marking in the image. By using the DGPS data collected for the imaged lane boundaries, the lane marking can be accurately placed with respect to the global coordinate frame.

By saving the data in a file with a specified format, it is possible to process the files and create a high accuracy geospatial database with minimal passes on each road, little intervention, and little processing time.

In order to validate the accuracy of the vision-based system, data was collected on two roads, State Highway 252 and McLeod County 2. State Highway 252 was chosen as a test route because it contains intersections and turn lanes, which can affect the mapping process and accuracy. McLeod County 2 has many sharp turns that can lead to large errors, which can distort the accuracy. The data collected on these two roads was compared to a set of fiduciary points that were specially collected for these tests. By positioning a DGPS antenna over the lane marking and collecting data, it was possible to collect accurate data of the lane marking which could be compared against the vision-based data collected. The accuracy of this system is actually the static accuracy of the DGPS unit, approximately 2-5 cm (0.8-2.0 inches) at $\pm 1\sigma$.

The vision-based data collected was fit using a least squares linear regression model. Each data point was fit to within a specified tolerance level of 5, 10, and 20 cm (2.0, 3.9, and 7.9 inches). This resulted in a reduced density map while maintaining accurate geometry. If the linear regression tolerance level is 10 cm (3.9 inches) or less, it is possible to reduce the number of data points one-fortieth and maintain a map that is accurate to within 20 cm (7.9 inches).

While the results are promising, there were some concerns when using computer vision. These include the possibility of false positives and negatives. Shadows, additional paint markings for intersections, etc., can skew the actual results and incorrectly shift the derived position. However, these happen infrequently, and were not found to be a problem. The data is filtered after acquisition, which can remove this type of inconsistent data. Because the image captured is nearly always a white lane marking on a dark (asphalt) or light (concrete) background and the lane marking orientation is known, many limiting factors of computer vision can be dealt with in software.

Having a nationwide correction signal for DGPS is not yet in place. While Minnesota has an extensive correction system in place for most of the state, there are many rural areas that do not yet receive the correction. Currently, this problem is being addressed by many DOTs using VRS corrections and the FHWA creating HA-NDGPS. In the future, this should not be a significant problem.

Since the system's accuracy relies on DGPS, it is the most limiting factor. There is also a reduction in the accuracy of the DGPS in urban areas when there is a reduced amount of sky available due to buildings, bridges, etc. These are typically not issues in rural areas where most lane departure fatalities occur. Roads on mountainsides, in canyons, or in deep valleys may be problematic because of limits in the availability of a reasonable number of satellites in the sky to achieve an accurate solution. Alternative solutions may be more appropriate in these locations. Focusing on the vast majority of rural areas in which this is not a problem could still eliminate most rural lane departure crashes. It is highly likely that with the deployment of next generation GPS satellites, such concerns will be significantly reduced.

In conclusion, the system presented in this paper has the ability to accurately capture the road geometry for a lane-level accurate geospatial database. A geospatial database with this type of accuracy can alert a driver to a potential lane departure. By using this system, it is feasible to collect and process accurate data in an efficient manner. This can produce a high accuracy geospatial database with little post-processing work in less time than those previously employed.

References

[1] Minnesota Motor Vehicle Crash Facts, Minnesota Department of Public Safety – Office of Traffic Safety, Minnesota, 2003, http://www.dps.state.mn.us/ots/crashdata/crash_facts.asp.

[2] E. Baltsavias, C. Käser. DTM and Orthoimage Generation – A Thorough Analysis and Comparison of Four Digital Photogrammetric Systems. *ISPRS Commision IV Symposium on GIS – Between Visions and Applications* Vol. 32/4, Stuttgart, Germany, Sept 1998.

[3] D. McNabb. Enhancing LIDAR with Digital Imagery. In *Proceedings of International Workshop on Three Dimensional Analysis of Forest Structure and Terrain Using LiDAR Technology*, Victoria, British Columbia, Canada, March 2002.

[4] Alan Forghani, Shanti Reddy, Craig Smith. Evaluating SPOT-5 Satellite Imagery for National Mapping Division's Topographic Mapping Program. *Proceedings of the Spatial Sciences Conference*, pages 1-12, Canberra, Australia, September 2003.

[5] C. Wilson, S. Rogers, P. Langley. Method and System for Autonomously Developing or Augmenting Geographical Databases by Mining Uncoordinated Probe Data. United States Patent 6,385,539, Filed August 13, 1999.

[6] S. Rogers. Creating and Evaluating Highly Accurate Maps with Probe Vehicles. In *Proceedings of the 2000 IEEE Intelligent Transportation Systems*, pages 125-130, Dearborn, MI, October 2000.

[7] Enhanced Digital Mapping Project Final Report. *Federal Highway Administration Cooperative Agreement Number DTFH61-01-X-00014*, November 2004.

[8] Jan Juslén. National Road and Street Database Development in Finland. *Finncontact-Quarterly Newsletter of the Finnish Highway Transportation Technology Center*, Vol. 11 No. 4, December 2003.

[9] Test Map Realisation and Results, NextMAP Project Final Report. *European Commission's 5th Framework Information Society Technologies IST-1999-11206*, January 2002.

[10] Final Enhanced Map Database Requirements, NextMAP Project Final Report. *European Commission's 5th Framework Information Society Technologies IST-1999-11206*, February 2002.

[11] D. Grejner-Brzezinska, C. Toth. Precision Mapping of Highway Linear Features. In *Geoinformation for All, Proceedings, XIXth ISPRS Congress*, pages 233-240, Amsterdam, Netherlands, July 2000.

[12] Manfred D.M. Sever, Frank A, Artés. Using Inertially-Aided Real-Time Kinematic Technology as a Land-Based Mapping Tool. In *7th Annual International Conference Map India 2004*, New Delhi, India, January 2004.

[13] Bryan J. Newstrom. Real Time High Accuracy Geospatial Database for Onboard Intelligent Vehicle Applications. Master's thesis, Mechanical Engineering Department, University of Minnesota, November 2000.

[14] Bryan Newstrom, Craig Shankwitz, and Max Donath. Real Time High Accuracy Geospatial Database for Onboard Intelligent Vehicles. United States Patent Application 10/091, 182, Filed March 2002.

[15] H.M. Lim. A GPS-based Heads Up Display System for Driving Under Low Visibility Conditions. Master's thesis, Mechanical Engineering Department, University of Minnesota, 1999.

[16] H.M. Lim, B. Newstrom, C. Shankwitz, M. Donath. A Heads Up Display Based on a DGPS and Real Time Accessible Geospatial Database for Low Visibility Driving. In *Proceedings of the 12th International Meeting of the Satellite Division of the Institute of Navigation (ION GPS 1999)*, Nashville, Tennessee, September 1999.

[17] H.M. Lim, B. Newstrom, C. Shankwitz, M. Donath. A Conformal Augmented Head Up Display for Driving Under Low Visibility Conditions. In *Proceedings of the 5th International Symposium on Advanced Vehicle Control (AVEC 2000)*, Ann Arbor, Michigan, August 2000.

[18] Pratop Misra, Per Enge. Global Positioning System: Signals, Measurements, and Performance. Ganga-Jamuna Press, 2004.

[19] Vassilios Morellas, Ted Morris, Lee Alexander, Max Donath. Preview Based Control of a Tractor Trailer Using DGPS for Preventing Road Departure Accidents. Proceedings of the IEEE Conference on Intelligent Transportation Systems, ITSC '97, Boston, MA, November 1997.

[20] M. Rakauskas, N. Ward, C. Shankwitz, A. Gorjestani, M. Donath. System Performance and Human Factors Evaluation of the Driving Assistive System (DAS): Supplemental Track Test Evaluation. Final Report, Minnesota Dept. of Transportation, Report No. 2004-12, December 2003, http://www.dot.state.mn.us/guidestar/pdf/ivihwy7/closedcourseresults2.pdf.

[21] Romuald Aufrére, Christoph Mertz, Charles Thorpe. Multiple Sensor Fusion for Detecting Location of Curbs, Walls, and Barriers. In *Proceedings of the IEEE Intelligent Vehicles Symposium (IV2003)*, Columbus, Ohio, June 2003.

[22] Alberto Broggi, Alessandra Fascioli. Artificial Vision in Extreme Environments for Snowcat Tracks Detection. In *IEEE Transactions on Intelligent Transportation Systems Vol.3, No. 3*, pages 162-172, September 2002.

[23] R. Bracewell. *The Fourier Transform and Its Applications, 3rd ed.*, New York: McGraw-Hill, 1999.

[24] I. I. Hirschman, D. V. Widder. *The Convolution Transform.* Princeton, NJ: Princeton University Press, 1955.

[25] D. Phillips. *Image Processing in C: Analyzing and Enhancing Digital Images*. R & D Publications, Inc., 1994.

[26] P.V.C. Hough, Machine Analysis of Bubble Chamber Pictures, International Conference on High Energy Accelerators and Instrumentation, CERN, 1959.

[27] Road Design Manual, Minnesota Department of Transportation, 2004.

[28] Michael Sergi, Bryan Newstrom, Alec Gorjestani, Craig Shankwitz, and Max Donath. Dynamic Evaluation of High Accuracy Differential GPS. In *Proceedings of the Institute of Navigation 2003 National Technical Meeting*, pages 581-592, Anaheim, California, January 2003.

[29] Lee Alexander, Pi-Ming Cheng, Max Donath, Alec Gorjestani, Bryan Newstrom, Craig Shankwitz, Walter Trach, Jr. DGPS-based Lane Assist System for Transit Buses. In *The 7th IEEE International Conference on Intelligent Transportation Systems*, Washington D.C., October 2004.

[30] M. Rakauskas, N. Ward, C. Shankwitz, A. Gorjestani, M. Donath. System Performance and Human Factors Evaluation of the Driving Assistive System (DAS) – Special Vehicle Field Operational Test. Final Report, Minnesota Dept. of Transportation, Report No. 2004-09, December 2003, http://www.dot.state.mn.us/guidestar/pdf/ivihwy7/operationalresults1.pdf.

[31] A.L. Edwards. *An Introduction to Linear Regression and Correlation, 2nd ed.,* San Francisco, CA: W. H. Freeman & Co. (Sd), June 1984.

[32] C. Lawson and R. Hanson. *Solving Least Squares Problems*, Englewood Cliffs, NJ: Prentice-Hall, 1974.

[33] Support of the System Test and Analysis Program for the Nationwide Differential Global Positioning System Modernization Program – Phase I High Accuracy-Nationwide Differential Global Positioning System Report. FHWA-RD-02-110, July, 2002.

Appendix A

FHWA Highway Statistics – 2003

Table A.1: Public road length – 2003 miles by functional system – FHWA Table HM-20 (Only the rural mileage shown. The original table includes both rural and urban mileage.)

(Tables found at: http://www.fhwa.dot.gov/policy/ohim/hs03/re.htm)

	RURAL						
State	Interstate	Other Principle Arterial	Minor Arterial	Major Arterial	Minor Collector	Local	Total
Alabama	604	2,077	3,625	11,979	6,338	48,853	73,476
Alaska	1,012	805	442	1,383	1,055	7,463	12,160
Arizona	980	1,141	1,260	4,236	2,122	25,890	35,629
Arkansas	467	2,167	2,997	12,489	6,659	62,954	87,733
California	1,357	3,751	7,002	13,170	8,712	49,935	83,927
Colorado	687	2,263	3,389	5,818	8,919	47,617	68,693
Connecticut	43	164	262	917	362	4,372	6,120
Delaware	-	214	122	554	166	2,809	3,865
Dist. of Columbia	-	-	-	-	-	-	-
Florida	951	3,501	2,830	4,358	4,052	36,204	51,896
Georgia	806	2,807	5,586	13,679	7,510	57,589	87,977
Hawaii	6	179	317	364	131	1,184	2,181
Idaho	526	1,721	1,281	5,431	4,065	29,493	42,517
Illinois	1,508	2,599	4,778	14,143	3,490	75,001	101,519
Indiana	852	1,742	2,235	10,760	9,699	48,709	73,997
Iowa	628	3,459	3,927	14,246	16,194	64,357	102,811
Kansas	691	3,147	4,302	23,053	9,266	83,960	124,419
Kentucky	553	2,310	1,740	6,132	8,914	45,380	65,029
Louisiana	612	1,122	1,766	5,049	3,679	34,759	46,987
Maine	313	788	1,043	3,263	2,233	12,420	20,060
Maryland	184	445	832	1,635	1,653	9,159	13,908
Massachusetts	91	164	406	1,138	775	5,335	7,909
Michigan	611	2,567	3,836	15,996	5,936	58,188	87,134
Minnesota	683	3,596	6,416	16,286	11,759	76,944	115,684
Mississippi	481	1,826	3,709	11,613	2,289	43,526	63,444
Missouri	807	3,134	3,440	17,910	5,455	76,363	107,109
Montana	1,130	2,618	2,989	7,058	8,988	43,914	66,697
Nebraska	429	2,724	4,194	11,525	8,826	59,733	87,431
Nevada	480	1,396	721	2,185	2,272	21,196	28,250
New Hampshire	184	481	505	1,253	1,247	8,924	12,594
New Jersey	65	254	313	917	389	5,473	7,411
New Mexico	868	1,831	1,982	3,885	2,629	45,944	57,139
New York	946	1,850	4,131	6,131	10,374	48,547	71,979
North Carolina	645	2,220	2,992	8,668	7,333	55,892	77,750
North Dakota	531	2,933	2,514	11,448	-	67,522	84,948
Ohio	724	1,935	2,655	11,201	6,687	57,058	80,260

Oklahoma	682	2,316	2,679	21,233	3,008	67,669	97,587
Oregon	582	2,817	2,252	8,977	7,184	33,072	54,884
Pennsylvania	1,107	2,066	4,642	7,381	7,415	60,123	82,734
Rhode Island	21	48	66	145	125	817	1,222
South Carolina	682	1,487	3,687	8,128	3,782	37,779	55,545
South Dakota	629	2,544	3,351	12,431	6,596	55,873	81,424
Tennessee	682	1,785	3,346	5,132	10,754	46,401	68,100
Texas	2,192	6,851	9,631	36,035	18,300	145,691	218,700
Utah	769	1,012	1,535	3,322	3,947	23,942	34,527
Vermont	280	317	733	2,007	912	8,728	12,977
Virginia	669	1,444	3,461	9,365	2,462	32,830	50,231
Washington	501	2,097	1,993	8,389	6,377	43,449	62,806
West Virginia	455	1,081	1,469	5,999	2,331	22,468	33,803
Wisconsin	516	3,254	4,894	13,333	6,311	64,669	92,977
Wyoming	826	1,988	1,318	2,538	7,842	10,466	24,978
U.S. Total	32,048	97,038	135,596	424,288	267,524	2,076,644	3,033,138
Puerto Rico	31	48	71	378	272	2,355	3,155
Grand Total	32,079	97,086	135,667	424,666	267,796	2,078,999	3,036,293

Table A.2: Federal-aid highway length – 2003 miles by traffic lanes and access control – FHWA Table HM-36 (Only the rural mileage shown. The original table includes both rural and urban mileage.)

Traffic Lanes and Access Control	National Highway System		Other Federal-Aid Highways		All Federal-Aid Highways	
	Miles	Percent	Miles	Percent	Miles	Percent
Rural:						
One-way streets	42	0.0	123	0.0	165	0.0
2 lanes	57,312	49.5	558,460	97.9	615,772	89.7
3 lanes	1,671	1.4	1,035	0.2	2,706	0.4
4 or more lanes – undivided	3,374	2.9	3,979	0.7	7,353	1.1
Divided highways – 4 or more lanes: Degree of access control:						
None	10,977	9.5	5,784	1.0	16,761	2.4
Partial	6,481	5.6	1,145	0.2	7,626	1.1
Full	35,864	31.0	195	0.0	36,059	5.3
Total Rural	115,721	100.0	570,721	100.0	686,442	100.0