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Advanced BRT Volume II: Innovative Technologies for Dedicated Roadways

Final Report

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16. Abstract (Limit: 250 words)
Presented herein is a novel approach to vehicle positioning using RFID technology (Vehicle Positioning System, or VPS). By installing in the road RFID tags encoded with road name or other designation, the specific lane, the direction of travel, and the longitudinal distance from a known reference, a vehicle outfitted with an RFID tag reader can determine its position each time it passes over and reads a tag, thus, providing precisely the information needed for many ITS applications – the longitudinal position of a vehicle in a particular lane on a particular road of the transportation network.

Knowledge of lane of travel and distance from a known reference provided by VPS enables many transit applications, including headway control of bus platoons, merge/lane change assistance, rear-end collision avoidance, and bay mark-up applications. For lane assist systems, VPS and a lateral positioning system can augment DGSP in urban areas, providing seamless operation where DGPS accuracy is insufficient for lane keeping.

This research focused on designing and building a prototype VPS using existing third party RFID hardware. The hardware was evaluated and characterized to determine if it could be used to create a viable, robust VPS. After the development and characterization of the positioning system, an implementation of a rear-end collision avoidance system was built to demonstrate the use of VPS. Finally, a more sophisticated rear-end collision avoidance system was designed and simulated, after which its implications to the accuracy specifications for VPS were analyzed.

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The authors would like to thank Metro Transit, in particular, Steve McLaird and Lenny Pawlek for keeping the Technobus Research Vehicle clean and in terrific working order long past its typical service life. Steve has allowed the use of the bus for numerous demonstrations and meetings, allowing the IV Lab to show that this technology is really viable for transit applications. Lenny and his staff in the Heywood Maintenance Garage have kept the bus in working order, fueled, and clean for both research activities and demonstrations. Without their help, this program would have never made it to the next step.

Their support is greatly appreciated.

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Executive Summary

In the United States, a number of transit agencies are either now operating Bus Rapid Transit (BRT) systems or are in the process of initiating this service. For example, Twin Cities Metro Transit operates a BRT system using a network of more than 200 miles of road shoulders to allow bus passage during periods of high traffic congestion. Lane Transit in Eugene, Ore., and the Cleveland Regional Transit Authority are building BRT systems, both of which are likely to use Lane Assist Technology on dedicated, narrow lanes.

To provide a driver with assistance with the guidance of transit vehicles on narrow rights-of-way, the Intelligent Vehicles Lab at the University of Minnesota (IV Lab) has developed and demonstrated a comprehensive driver assist system designed to ease driver stress by providing both lane keeping and collision avoidance assistance. The system uses DGPS for vehicle positioning and heading measurements, a high-accuracy digital geospatial database that provides the location of roads and boundaries, and a combination of vehicle mounted radar and laser scanners to determine the presence and location of obstacles that may pose a collision threat to the bus. Feedback to the driver is provided through a graphics-based Head Up Display (or HUD, for the forward view) and virtual mirrors (side and forward views), a tactile seat, and a haptic steering wheel. The Head Up Display provides a conformal, augmented view of the forward landscape, including lane boundaries and the location of obstacles. The virtual mirrors are laser-scanner driven displays, and show the presence and location of both vehicles and passengers on the left and right sides of the bus, respectively. The tactile seat vibrates when a lane departure event is sensed; vibrations occur on either the left or right side of the seat if the bus is departing the present lane of travel to the left or right, respectively. The haptic steering wheel acts continuously to pull the bus to the center of the lane should the bus drift from the center of the lane or shoulder.

Two limitations of the system as it exists today are addressed by this report. First, the system positioning is provided by DGPS. Should the view of GPS satellites be restricted or blocked entirely, the system becomes inoperable. This causes occasional system outages in suburban areas and substantial outages in urban areas. Second, the range of the laser scanners is limited. Problems with this limited range are manifest in merge/exit situations with buses operating on bus-only shoulders. Bus drivers cannot see merging or exiting traffic, which produces conflicts at merge points. These conflicts are compounded by ramps transporting vehicles from either above or below roadway grade. The bus-mounted laser scanner operates in a single plane, making detection of these merging vehicles more difficult.

These two system limitations are addressed herein. First, to deal with the loss of DGPS outages, an augmentation of the DGPS positioning system with VPS (the subject of volume 1) is proposed.

Volume One of the two-volume report describes the development and the performance of a technology known as VPS (Vehicle Positioning System). (VPS is described in a separate volume because VPS has a myriad of applications in addition to augmenting GPS for vehicle guidance and driver assistance applications.) VPS, which utilizes RFID technology, provides lane-of-travel information (i.e., “rightmost lane of east bound I-94”) and longitudinal information (i.e., “203 meters past mile marker 157”) on a coarse grid. Finer longitudinal

information can be obtained by on-board odometry provided by either the vehicle odometer, or if more accuracy is required, a non-contact odometer.

Although VPS provides lane-of-travel information, and a measure of the distance from a reference marker along that lane-of-travel, this information is insufficient for the lane-keeping task. To maintain proper lane position, the lateral position within a lane is required.

Described in this volume is a design which uses VPS and on-board laser scanners to determine a sufficiently accurate bus position which can enable the IV Lab lane-assist system to function in areas where GPS signals are either unavailable or too inaccurate to provide DGPS position estimates. The system is designed to operate in either a dedicated, barrier separated lane, a mixed traffic lane located adjacent to a curb (with a clear view of the curb (i.e., no parked cars)), or on a bus-only shoulder that has a curb or barrier demarking the edge of the shoulder. Under these conditions, an on-board laser scanner is used to measure the distance of the bus from the separating barrier or the curb. This lateral distance, combined with the lane-of-travel information provided by VPS, allows the bus to "follow" the curb at a specified lateral position from the curb. The "map" of desired optimal curb distance as a function of distance along the lane becomes the lateral control reference signal.

The design of this system and initial results of the laser scanner based curb measurement device are described in Chapter Two. The design of the VPS-laser scanner system will serve as the basis for a follow-on research program, the goal of which is to implement and test the design described herein.

To address the limitation of fixed range, vehicle-based laser scanners used for obstacle detection and positioning, a vehicle-infrastructure cooperative approach has been implemented and demonstrated. Although at the present time, bus-only shoulder operations are essentially limited to Minnesota (Georgia and New Jersey are working to initiate bus-only shoulder programs), the use of shoulders on limited access facilities creates a problem for both bus drivers and drivers of other vehicles using entrance and exit ramps. During bus-only shoulder operations, a bus traveling on the shoulder has its path crossed by both entering and exiting traffic. Under normal (i.e., non-bus-only shoulder uses) conditions, the bus and entering/exiting traffic are not forced to share the shoulder, thereby minimizing vehicle-to-vehicle conflicts. The difficulty of this situation is further increased by the limited side visibility associated with bus mirrors and the fact that entrance and exits often involve short approaches and changes in grade. It is difficult for bus drivers to even see approaching traffic; once detected, it is more difficult to determine whether approaching traffic will accelerate or decelerate.

To assist a driver through the crossover area, an adaptation of the IV Lab intersection surveillance system has been used to provide a driver information regarding vehicles entering the traffic stream. (The driver is left to use his or her left side mirror and the windshield to determine whether a following vehicle will pass by and cut in front of the bus, or will wait and exit behind the bus). For this application, a high accuracy geospatial database of the entrance ramp is created. With this database, a radar placement software tool is used to determine the optimal location for the radar used to monitor the traffic traveling on the entrance ramp. This same map is loaded onto the bus for the purpose of real-time visualization.

Radar data is broadcast to the bus wirelessly using 802.11b hardware. (IEEE 802.11b hardware was used because it is readily available; DSRC radios can be used when they become available.) This radar data allows the location of vehicles on the ramp to be seen by the driver on an on-board display. Radar information on this display is integrated with bus position data, allowing the driver to compare his/her position with the traffic entering from the ramp. This allows a driver to determine whether to accelerate or decelerate to avoid a conflict with the vehicle approaching from the on-ramp.

The vehicle-infrastructure cooperative system was designed and tested during June 2006 using the on-ramp that carries traffic from eastbound Minnesota Highway 610 onto southbound Minnesota Highway 252. The design of the system and the results of the remote sensing are provided in Chapter Three. The testing was successful, and the test bus driver was able to use the in-vehicle display showing ramp traffic to adjust his speed and safely merge with traffic entering highway 252 from highway 610.

Finally, the final goal of any IV Lab project is deployment. As a means to this end, Minnesota Valley Transit (MVTA) has expressed interest in the deployment of a small fleet of buses that will operate with a driver assistive system. Cedar Avenue, from Apple Valley, MN, to the interection of Cedar Avenue and Minnesota Trunk Highway 62 (aka, the “Crosstown”) is the target corridor upon which the fleet of buses will run. The advent of a new working relationship with MVTA may signal the start of an operational test that will provide data to determine the true cost:benefit associated with a lane assistance system.

Chapter 1
Introduction

In the United States, a number of transit agencies are either presently operating Bus Rapid Transit (BRT) systems or are in the process of initiating this service. For example, Twin Cities Metro Transit operates a BRT system using a network of more than 200 miles of road shoulders to allow bus passage during periods of high traffic congestion. Lane Transit in Eugene, Oregon, and the Cleveland Regional Transit Authority are building BRT systems, both of which are likely to use Lane Assist Technology on dedicated, narrow lanes.

To provide a driver with assistance with the guidance of transit vehicles on narrow rights-of-way, the Intelligent Vehicles Lab at the University of Minnesota (IV Lab) has developed and demonstrated a comprehensive driver assist system designed to ease driver stress by providing both lane keeping and collision avoidance assistance. The system uses DGPS for vehicle positioning and heading measurements, a high-accuracy digital geospatial database which provides the location of roads and boundaries, and a combination of vehicle mounted radar and laser scanners to determine the presence and location of obstacles which may pose a collision threat to the bus. Feedback to the driver is provided to the driver through a graphics-based Head Up Display (or HUD, for the forward view) and virtual mirrors (side and forward views), a tactile seat, and a haptic steering wheel. The Head Up Display provides a conformal, augmented view of the forward landscape, including lane boundaries and the location of obstacles. The virtual mirrors are laser-scanner driven displays, and show the presence and location of both vehicles and passengers on the left and right sides of the bus, respectively. The tactile seat vibrates when a lane departure event is sensed; vibrations occur on either the left or right side of the seat if the bus is departing the present lane of travel to the left or right, respectively. The haptic steering wheel acts continuously to pull the bus to the center of the lane should the bus drift from the center of the lane or shoulder.

Two limitations of the system as it exists today are addressed by this report. First, the system positioning is provided by GPS. Should the view of GPS satellites be restricted or blocked entirely, the system becomes inoperable. This causes occasional system outages in suburban areas and substantial outages in urban areas. Second, the range of the laser scanners is limited. Problems with this limited range are manifest in merge/exit situations with buses operating on bus-only-shoulders. Bus drivers cannot see merging or exiting traffic, which produces conflicts at merge points. These conflicts are compounded by ramps transporting vehicles from above or below roadway grade. The laser scanner operates in a single plane, making detection of these merging vehicles more difficult.

Volume One of the two-volume report describes the development and the performance of a technology known as VPS (Vehicle Positioning System). (VPS is described in a separate volume because VPS has a myriad of applications in addition to augmenting GPS for vehicle guidance and driver assistance applications.) VPS, which utilizes RFID technology, provides lane-of-travel information (i.e., “rightmost lane of east bound I-94”) and longitudinal information (i.e., “203 meters past mile marker 157”) on a coarse grid. Finer longitudinal information can be obtained by on-board odometry provided by either the vehicle odometer, or if more accuracy is required, a non-contact odometer.

Although VPS provides lane-of-travel information and a measure of the distance from a reference marker along that lane-of-travel, this information is insufficient for the lane keeping task. To maintain proper lane position, the lateral position within a lane is required.

The first objective of the research described herein is the development of technologies which can be used to augment DGPS when an obstruction of the view of the GPS satellites prevents accurate positioning of a vehicle. To leverage present IV Lab capabilities, the augmentation systems will be amendable for use with present IV Lab technologies, primarily the geospatial database which describes the geometry of the roads and shoulders traveled by IV Lab vehicles.

Chapter 2 describes the design of a system which will provide lane assistance in environments where DGPS is unavailable. This system is designed for use in a barrier separated dedicated lane or in a mixed traffic lane which operates adjacent to and has an unobstructed view of the curb. The proposed system uses VPS to determine the present lane of travel, and distance along that lane from a known reference point. This provides the means to determine a coarse position of the bus.

A coarse position is insufficient for lane assistance and vehicle guidance applications. For passenger cars, on-board odometry can provide a more accurate longitudinal position (passenger car odometry is typically exhibits less than 1% error). Because transit buses have no accessible on-board odometry (transit buses typically rely on hub odometers for accumulated distance measurement), a high accuracy odometer is needed to determine distance traveled between VPS reference points. In this chapter, a means to provide accurate distance measurements between VPS RFID tags is provided.

VPS cannot provide a lateral position within a lane measurement. Chapter 2 also discusses the use of scanning laser sensors to identify the presence and location of fixed geospatial elements which can be used to determine lateral position in a lane. In prior applications, scanning laser sensors are used to detect both other vehicles (on the left side of the bus) and passengers entering and leaving the bus (right side of the bus) in virtual mirror applications. Using these same sensors for both obstacle detection and vehicle guidance leverages capability, providing greater functionality for a lower price.

The second objective of the research is the development and testing of a vehicle-infrastructure cooperative system designed to provide bus drivers information regarding vehicles merging onto the roadway from entrance ramps. Shoulders are typically crossover points at entrance ramps, and are traveled only briefly by vehicles making the transition from the ramp to the highway. Buses traveling on shoulders through the normal path of merging vehicles impede the natural flow of traffic across the shoulder. Moreover, entrance ramps typically involve grade changes; bus drivers using shoulders have poor sight lines to the entrance ramps, and often cannot see merging vehicles. Without good sightlines, the bus driver has does not know whether to maintain speed, accelerate, to decelerate to avoid a collision with merging traffic.

Chapter Three describes a vehicle-infrastructure sensing and display system designed to reduce ramp conflicts. A remote sensing system which allows a bus driver to “see” the on-ramp and the location of vehicles traveling on it was developed and tested. Optimally located radar connected to a wireless communication device broadcast the presence, location, and speed of vehicles on the on-ramp. This information is broadcast in real time to the bus, and the position and speed of both the vehicles on the ramp and the bus on the shoulder are displayed graphically to the bus driver. Presented with this information, the bus driver can adjust the speed of the bus to avoid conflict, and allow a smooth transition through the common area.

The report concludes with recommendations for further research activities, some of which have begun. The IV Lab has developed a research relationship with Minnesota Valley Transit Administration (MVTA) which is aimed at deployment of MVTA buses equipped with lane assist technology. These buses would support transit operations from the south metro area (i.e., Apple Valley) into downtown Minneapolis for routes using Cedar Avenue, the Crosstown (Minnesota Trunk Highway 62), and I-35W. MVTA’s vision for the near term includes a field operational test of these of five buses equipped with lane assist technology.

Chapter 2
Vehicle Guidance Technologies to Augment GPS

This chapter describes an integrated system designed to provide lane assistance in urban areas where GPS signals are unavailable due to a limited view of the sky or because of excessive multi-path caused by modern building designs. The system uses two separate technologies to accurately determine lane position; VPS provides lane-level position information along the traveled route; laser scanners are used to provide lateral position estimates within the lane as the bus travels along its desired route. These two technologies, integrated with an appropriate geospatial database to provide guidance references, will enable a lane assist system in a controlled environment. Descriptions of the operating environment, sensors, and integration process are provided below.

Assumed Operating Conditions.

GPS provides ubiquitous positioning capability, provided that a sufficient number of satellites are visible to the GPS receiver antenna and that the signals received by the GPS receiver are of sufficient quality (i.e., not affected by multipath) to provide a solution. In urban areas, especially those in downtown areas, GPS signals are typically of insufficient quality to support accurate position measurements.

The system proposed herein is designed to deal specifically with poor urban performance. The following set of assumptions describes the conditions under which the GPS augmentation system will function. These assumptions will enable the VPS-laser scanner integrated system to provide sufficient positional accuracy to enable continuous lane assistance.

This system requires one of two types of lanes: either a physically separated, dedicated lane (like that used by the Curtiba system in Bogota, Columbia) or a mixed traffic lane which provides a clear view of the curb at all times (i.e., parking is not allowed adjacent to the curb). Mixed traffic lanes with a clear view of the curb are quite common (see Figure 1 and Figure 2 below.). In both situations, a clear view of the barrier and/or curb provides a means with which to provide a measurement of the lateral position of the bus with respect to its present lane of travel.

Lane assistance is required (or useful) when lanes of travel are narrow. Rights of way for lanes passing through intersections are wider than operational lanes because barriers or curbs disappear within the intersection region. In these situations, the lack of a lateral reference does not reduce the utility of the lane assist system because a driver has a wide area in which to guide the bus.

Figure 1. Example of dedicated lanes for Bus Rapid Transit. This example is from the Curtiba system in Bogota, Columbia.

Figure 2. **Mixed traffic lane in an urban setting with no parking and a view of the curb (Orange Line, Los Angeles).**

VPS System Overview.

The VPS system is described in full detail in Volume One [1.]. However, an overview of the VPS system, taken from [2.] is provided herein to provide a the context for the reader not familiar with the VPS System.

The VPS system utilized RFID technology, and consists of two primary components: RFID tags encoded with relevant information, and an RFID reader

Inexpensive, passive RFID tags store encoded information, which is transferred to the reader when it comes in close proximity to the tag. A typical RFID system involves many tags and a reader, where the reader is used to gather information from each of the tags. Figure 1 shows a simple demonstration of how an RFID system works [3.].

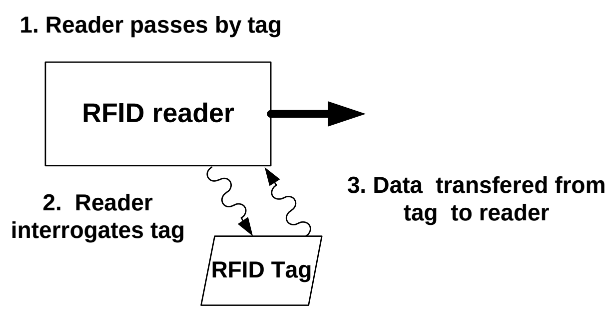

Figure 3: Demonstration of VPS concept using passive RFID technology. RFID reader excites tag within read range, and RFID tag information decoded by RFID reader.

By installing RFID readers on vehicles, and by placing inexpensive RFID tags along a road, moving vehicles are able to acquire the data encoded in the tags' memory. This simple concept facilitates not only lane-level vehicle positioning, but also a multitude of potential applications ranging from lane change warning to traffic signal priority.

In urban areas, GPS technology has proven itself insufficiently accurate to unambiguously determine the lane in which the vehicle is traveling. VPS is specifically designed for this task, and enables a number of applications where a global position reference, in the sense of GPS, is not required, but where accurate, lane-level positioning is.

To perform basic lane-level positioning, RFID tags encoded with lane position (lane ID tags) are placed down the center of a lane, and an RFID reader (lane ID tag reader) is attached to a vehicle. As a vehicle passes over a lane ID tag, the lane ID tag reader acquires the lane position encoded in the tags.

Lane position includes a road identifier, lane identifier, direction of travel identifier, and longitudinal position. Table 1 shows a more detailed description of the data fields to be stored within the lane ID tags. It is worth noting that the information stored in each lane ID tag must include, but is not limited to these fields.

Table 1. Definition of lane ID tag memory fields.

Data	Description
Road identifier	Used to identify the name of the road being traveled. It stores either the name of the road, if memory permits, or an identifying code.
Lane identifier	Identifies the specific lane of travel based on a standard referencing scheme.
Direction of travel identifier	N,S,E,W,NE,NW,SE,SW, etc… The direction of travel indicator may indicate the actual direction of travel of the road, or the direction designation given to the road. Note that the actual direction of travel of a road, and its direction designation are not always the same.
Longitudinal distance.	Used to identify the distance from a reference point on the road being traveled. On an interstate highway, for example, the most recently passed mile marker can serve as the reference. Longitudinal distance can, for example, be the mile marker number plus the distance along the center of the lane from the tag to the mile marker.

Lane ID tags are installed at periodic intervals along the center of each lane of a roadway. The spacing of the tags, as well as which lanes are equipped with the tags, is governed by the application for which they are being used. For example, for high occupancy tolling (HOT) lane applications, where accurate longitudinal positioning is not required, requires tags farther apart than for the electronic brake light application, for which more accurate positioning is required. For bus guidance applications in urban areas, a lane ID tag density of 100 to 200 feet is likely adequate.

To determine distance along a lane, vehicles must be equipped with an RFID reader. The reader is mounted on the front of the bus, and reads the tag when it is within close proximity to it. Generation 1 RFID Tags have been shown to have a read rage of approximately 25 cm in a VPS application [1.]; recently introduced Generation 2 RFID are expected to have a much longer read range in the VPS application.

As a vehicle equipped with an RFID reader passes over a tag, the position of the reader antenna is known at that instant to within a given error bound. Measurement errors can arise from many sources, including

- Variance in the distance an RFID reader is able to initially successfully read the tag.

- Errors associated with the position encoded in the tag
- Missed or damaged tags

VPS provides position measurements only at discrete points along the roadway. If 50 tags are used per mile, the tag spacing is approximately 101 feet. Without VPS measurement augmentation, the accuracy provide by VPS is insufficient for vehicle guidance applications.

VPS Positioning Augmentation for Vehicle Guidance Applications.

Vehicle odometry can be used to improve positioning accuracy between RFID tags. The coarse accuracy provided by reading RFID tags alone is insufficient for lane assistance and vehicle guidance applications. For passenger cars, on-board odometry can provide a more accurate longitudinal position (passenger car odometry is typically exhibits less than 1% error). Because transit buses have no accessible on-board odometry (transit buses typically rely on hub odometers for accumulated distance measurement), a high accuracy odometer is needed to determine distance traveled between VPS reference points. In this chapter, a means to provide accurate distance measurements between VPS RFID tags is provided.

Non-contact odometry.

Transit buses typically are delivered without fuel gages or interior odometers. Instead, transit buses are equipped with Hub Odometers. These odometers are used to track bus mileages for maintenance, repair, and record keeping purposes. Hub odometers have low resolution (0.1 mile) and are sealed, without an interface to the outside world. Clearly, a separate means to determine distance traveled after passing over an RFID tag is needed to accurately position a bus in the lane.

A number of non-contact odometers and velocimeters were reviewed before a selecting and procuring a test unit. Two technologies are available for measuring true ground speed: full spectrum light and radar. Examples of each technology are provided below.

Visible Light.

- Correvit L-350 Aqua. This is a non-contact, single axis optical sensor designed to measure slip-free longitudinal vehicle dynamics. Product specifications are provided in Table 2 below. The sensor is designed primarily as a test instrument which is attached to the vehicle body prior to testing, and which is removed when testing has been completed. This system uses a halogen visible light source as a primary sensing signal.

  The Correvit sensor shows both excellent accuracy and linearity as well as the ability to measure distance on wet roads. However, for a bus guidance application in Minnesota, a few problems arise. First, the sensor is only rated for 5 – 80% non-condensing humidity. This poses a problem for buses forced to operate year-round in snow, rain, and humid conditions. Second, the Correvit system uses a halogen light as its source of energy for the distance measurement system. The dirt, grime, and crust which accumulates on the sides and undersides of a transit bus will cover the light source lens, reducing the amount of light which reaches the road. Moreover, the same dirt, grime, and crust which accumulated on the light source will also collect on the imaging source, reducing the amount of light available to activate the sensor. Both situations lead to conditions where vehicle speed or distance traveled measurements are unavailable.

- Correvit L-400. The Correvit L-400 is different from the Correvit L-350 in two primary areas. First, the height at which the L-400 can be mounted is higher than the L-350 sensor. The L-400 should be mounted at 400 mm above the road surface, +/- 100 mm. Second, the L-400 is not "Aqua" rated, meaning it will not provide reliably accurate results on wet or "puddled" pavement.

- Ono Sokki markets a sensor suite very similar to that offered by Correvit. The LC-3110 also uses a halogen light source for surface illumination, and is sensitive to the same conditions and problems at the Correvit L-350 and L-400 sensors. Performance specifications for the Ono Sokki LC-3110 are provided in

  The technology and limitations of the Ono Sokki LC-3110 are quite similar to that of the Correvit L-400. Similar to the L-400, the LC-3110 will not work on a mirrored (wet) surface.

Radar.

- GHM Engineering of Orem, UT, manufactures a radar-based true ground speed sensor for automotive applications. The sensor uses Ka Band radar with a center frequency of 35 GHz for sensor excitation. The radar sensor is insensitive to dirt, crust, and moisture on the radome, and works regardless of pavement moisture content.

  Performance specifications are provided in **Table 4** below.

Integration of odometry and VPS for accurate "along path" positioning.

With an accurate speed measurement, high sample rates, and relatively slow vehicle longitudinal dynamic capability, the estimation of the distance traveled along a bus lane or shoulder is straight forward to computer. The radar velocimeter provided by GMH Engineering provides speed data at 100 Hz. Because of the limited bus dynamic capability, this 100 Hz sample rate enables a simple Euler integration scheme to provide accurate distance traveled along the lane estimates at 100 Hz. The dataflow for this process is shown in Figure 4 below.

Table 2. Specifications for the Correvit L-350 Aqua Sensor. The 350 in"L-350" refers to preferred mounting height above the road surface; Aqua indicates the system will work with a wet road surface.

Speed range	0-250 kph (0-155 mph)
Distance resolution	1.5mm
Distance Linearity	<+/- 0.2%
Speed Linearity	<+/- 0.5%
Working distance and range	350 mm, +90 mm/-100 mm
Outputs	• CAN 2.0B, Motorola or Intel • Analog: Speed, 0 to +/- 10V • DIO: v (frequency), distance (count pulses) • USB 2.0 or RS232
Sensor Excitation	Halogen Light source
Humidity	5 – 80%, non-condensing

Table 3. Specifications for Ono Sokki LC-3110. It is important to note that the LC-3110 is unable to measure under the condition of mirrored road-surface such as a puddle.

Measurement range	120 to +390 km/h
Detector mounting height:	280 ±60 mm (height between the measurement surface and the detector tip)
Distance resolution:	10 mm/P
Pulse output	10 mm/P (TTL), 90° differential phase signal
Analog output	±20 mV/±1 km/h DC
White line detection signal	Analog signal (0 to 12 V DC)
Stop signal	TTL signal (Hi when stopped)
Light projector	12 VDC, 50 W (Life: Approx. 400 hours of continuous use)
Operating temperature range	10 to +40°C
Outer dimensions	180 (W) x 150 (H) x 88 (D) mm
Weight	Approx. 1.7 kg, LC-0130 mounting fixture (option): Approx. 3.1 kg

Table 4. Specification for GHM Engineering DRS 1000 True Ground Speed Sensor

Speed Measurement	0.5 – 300 MPH
Sensor Error	+/-(0.34%+.0023%/MPH)
Sensor Data Rate	100 Hz
Output:	0-5V square wave, 100 Hz/MPH
Microwave Characteristics	Freq.: 35.5GHZ, +/- 0.1 GHz Beam angle: +/- 6 degrees Average RF Power: 0.02W Effective Radiated Power: 0.98 W
Sensor Response	Locking Latency: 0.02 s Unlocking Latency: 0.05 s Sensor time constant: 0.025 s
Enclosure	Weather Resistant.

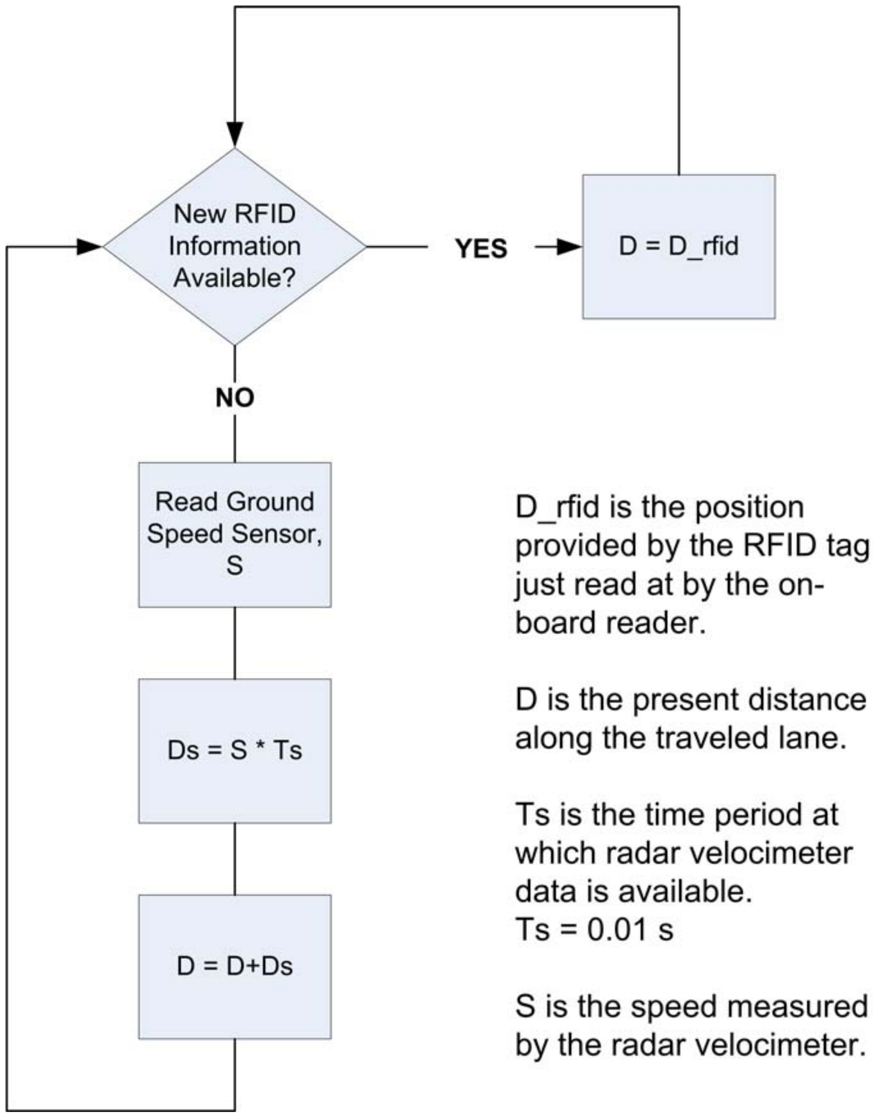

Figure 4. Flow chart for determining position along the lane of travel using VPS and on-board radar velocimetery. GMH Engineering sensor provides speed measurements at a 100 Hz rate.

Determination of lane lateral position error using VPS and Laser Scanner

Curb detection using non-contact sensors, primarily vision and laser scanners, has been address in a number of research papers. To put the work herein in the proper context, a review of previous work regarding curb following are presented.

Laser scanners and machine vision represent the two primary technologies used to locate curbs with respect to moving vehicles. These two technologies have been used alone, or have been integrated to improve robustness of the system.

In [4.], stereo vision is used to both detect the presence of a curb as well as determine the position and curvature of the curb with respect to the moving vehicle. Using commercial-off-the shelf stereo vision hardware, the authors were able to able to identify curbs at a rate of 4 Hz. This data rate, however, is well below the 10 Hz needed for robust vehicle guidance applications. Moreover, the approach is sensitive to camera misalignment. This sensitivity is problematic for a bus subject to impacts associated with day-to-day operations.

Vision and lasers have been integrated to produce a more robust, less sensitive method with which to detect the presence of and determine the distance to curbs. In [5.] and [6.], a system using a laser-based light striper and an image capturing device is used to determine the presence and location of a curb. A laser light strip source is mounted to the front of the vehicle of interest; the laser light stripe casts an eye visible line in front of the vehicle. A visible light camera, equipped with a filter which passes only light of the frequency of the laser light striper, is aimed at the laser light stripe. By passing only light filtered in a narrow frequency band, the image capture by the visible light sensitive CCD is essentially binary. The shape of the curb outlined by the laser striper is easily detected in the binary image; a pattern matching algorithm is used to identify the location of the curb in the image. An accurate camera calibration allows the position of the curb in the camera coordinate frame to be transformed to the position of the curb in the vehicle coordinate frame. Once in the vehicle coordinate frame, the path of the vehicle with respect to the curb can be tracked.

A less tightly coupled approach to vision and laser sensor integration is found in [7.]. In this system, a 2-D laser scanner is attached to the front of a vehicle with a slight downward tilt angle. An ideal road profile model (flat roadway, vertical “steps” representing the curb) is used in conjunction with an extended Kalman filter to determine the location of the curb boundary. The extended Kalman filter is needed to deal with both noisy reflections returned to the laser scanner as well as the singularities associated with the “steps” which represent the ideal curb model. The extended Kalman filter produces estimated of the lateral location of the curb with respect to the moving vehicle.

The 2-D laser scanner is integrated with information captured by a CCD camera to extract additional road features, namely centerline location and road curvature information. Previous estimates of curb position, d_{i-2}, d_{i-1} are used to project ahead in time the curb position at epoch d_i; curvature is estimated using these three data points. This curvature and position information then serves as a model to detect and position lane centerlines as captured by a forward looking CCD camera.

A similar approach to curb detection and location is presented in [8.]. In this approach, a CCD camera is used to detect the presence and location of the curb with respect to the moving vehicle; a 3-D scanning laser sensor is used to determine the vertical height of the curb. Upper and lower curb boundaries are determined using a vertical differential operator. Moving “across” the laser scanner field, vertical gradients are computed for each scan line.

The curb lower and upper positions are assumed to occur at the locations exhibiting the greatest gradient magnitude.

The approach taken herein utilizes an *a priori* curb profile information and a vertically mounted, 2-D laser scanner. The use of *a priori* curb profile information, where curb cross-section profiles are matched to distance traveled along a roadway and stored in an on-board database simplifies the estimation process, minimizing the need for a Kalman filter to determine curb presence and location. Because curb geometries are unlikely to change, changes to the database will be either infrequent or unnecessary.

In this application, a vertically mounted laser scanner is used to determine the presence and location (with respect to the bus) of the curb. See Figure 5 for details.

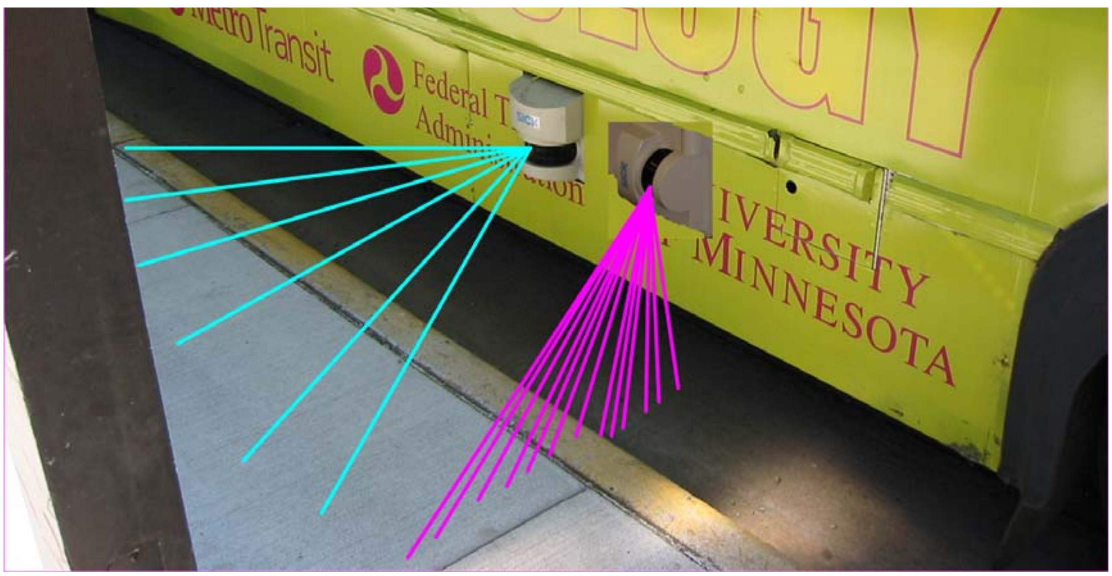

Figure 5. Representation of horizontal and vertical laser scanners mounted on the Metro Transit Technobus.

The horizontal scanner, actually mounted on the bus as shown with blue rays traced in Figure 5, is used to track the trajectory of passengers as they exit the bus. The laser scanner provides data for an in-vehicle display, the virtual mirror. The virtual mirror provides a driver the same information (although perhaps in a different format) that an optical mirror would. The motivation for the virtual mirror is to replace the optical mirror, which extends 25.5 cm past the right-side surface of the bus. Narrowing the width of the bus is equivalent to making the operational lane narrower.

A representation of a vertically mounted laser scanner is also shown in Figure 5. (The vertically mounted sensor was integrated into the side of the bus. However, the Technobus was decommissioned, and subsequently sold for scrap before a photo of the integrated vertical sensor was captured.) The laser scanner is used to determine both the presence and the position of the curb with respect to the bus.

A number of different curb geometries and curb profiles are used throughout the US. Examples of these geometries are shown in Figure 6. These models are used for the cross-correlation process.

A dynamic cross-correlator based on data returned from a vertically mounted laser scanner mounted on the side of a bus is used to determine the presence of and distance to a curb. The laser scanner captures the profile of the cross-section of the road-gutter-curb system adjacent to the bus. Once the profile is captured, a curb model is used as a reference for the cross-correlation process. The equation for a normalized cross-correlation is provided in Equation 1 below

$$(f * g)_i = \frac{\sum_j f_j^* g_{i+j}}{\sum_j f_j^* f_j}, \qquad (1)$$

where f_j is the reference curb model, and f_j^* is its conjugate transpose, and g_j is the present sensor reading.

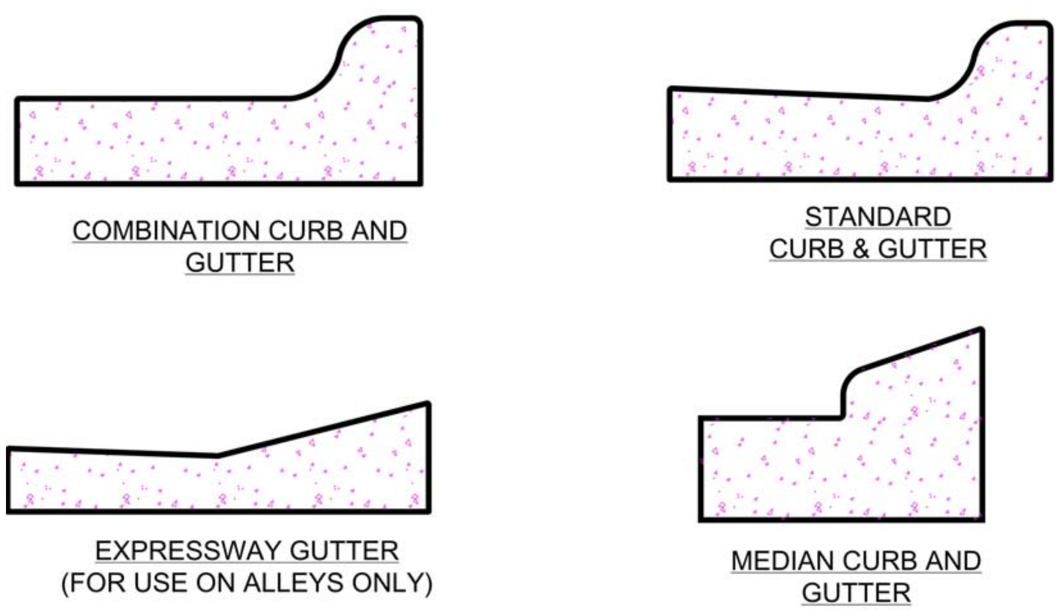

Figure 6. A few example cross-sections of various curb geometries used in the US. For cross-correlation methods, sharp corners represent the preferred geometry. However, with a proper curb model, the cross-correlation techniques can prove robust.

As an example, two curb models are provided as reference in Figure 7.

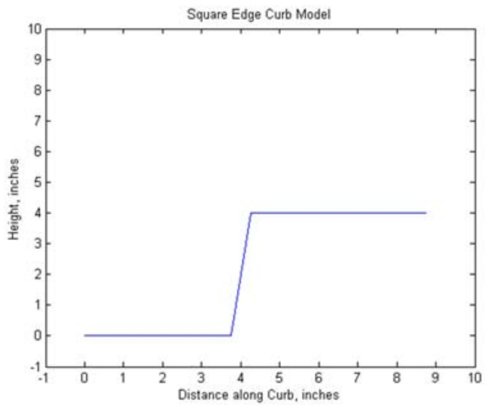

Figure 7. Reference curb models for cross-correlation.

Numerically, the curb models are represented as shown in Table 5. Other geometries can be represented in much the same way.

Table 5. Example numeric models for Square Edge and Round Edge Curbs.

	Square Edge Curb		Round Edge Curb	
i	x_i , in	f_i , in	x_i , in	f_i , in
1	0.00	0.00	0.00	0.00
2	0.25	0.00	0.25	0.00
3	0.50	0.00	0.50	0.00
4	0.75	0.00	0.75	0.00
5	1.00	0.00	1.00	0.00
6	1.25	0.00	1.25	0.00
7	1.50	0.00	1.50	0.00
8	1.75	0.00	1.75	0.00
9	2.00	0.00	2.00	0.00
10	2.25	0.00	2.25	0.00
11	2.50	0.00	2.50	0.00
12	2.75	0.00	2.75	0.00
13	3.00	0.00	3.00	0.00
14	3.25	0.00	3.25	0.00
15	3.50	0.00	3.50	0.00
16	3.75	0.00	3.75	0.00
17	4.00	2.00	3.95	0.00
18	4.25	4.00	4.15	0.01
19	4.50	4.00	4.35	0.04
20	4.75	4.00	4.55	0.09
21	5.00	4.00	4.75	0.17
22	5.25	4.00	4.95	0.27
23	5.50	4.00	5.15	0.40
24	5.75	4.00	5.35	0.57
25	6.00	4.00	5.55	0.80
26	6.25	4.00	5.75	1.13
26	6.50	4.00	5.95	2.00
28	6.75	4.00	6.15	2.87
29	7.00	4.00	6.35	3.20
30	7.25	4.00	6.55	3.43
31	7.50	4.00	6.75	3.60
32	7.75	4.00	6.95	3.73
33	8.00	4.00	7.15	3.83
34	8.25	4.00	7.35	3.91
35	8.50	4.00	7.55	3.96
36	8.75	4.00	7.75	3.99
36			7.95	4.00
38			8.45	4.00
39			8.95	4.00
40			9.45	4.00

Once the curb model f_i has been determined, the cross-correlation process can be executed. The process will be explained, using Figure 8 below.

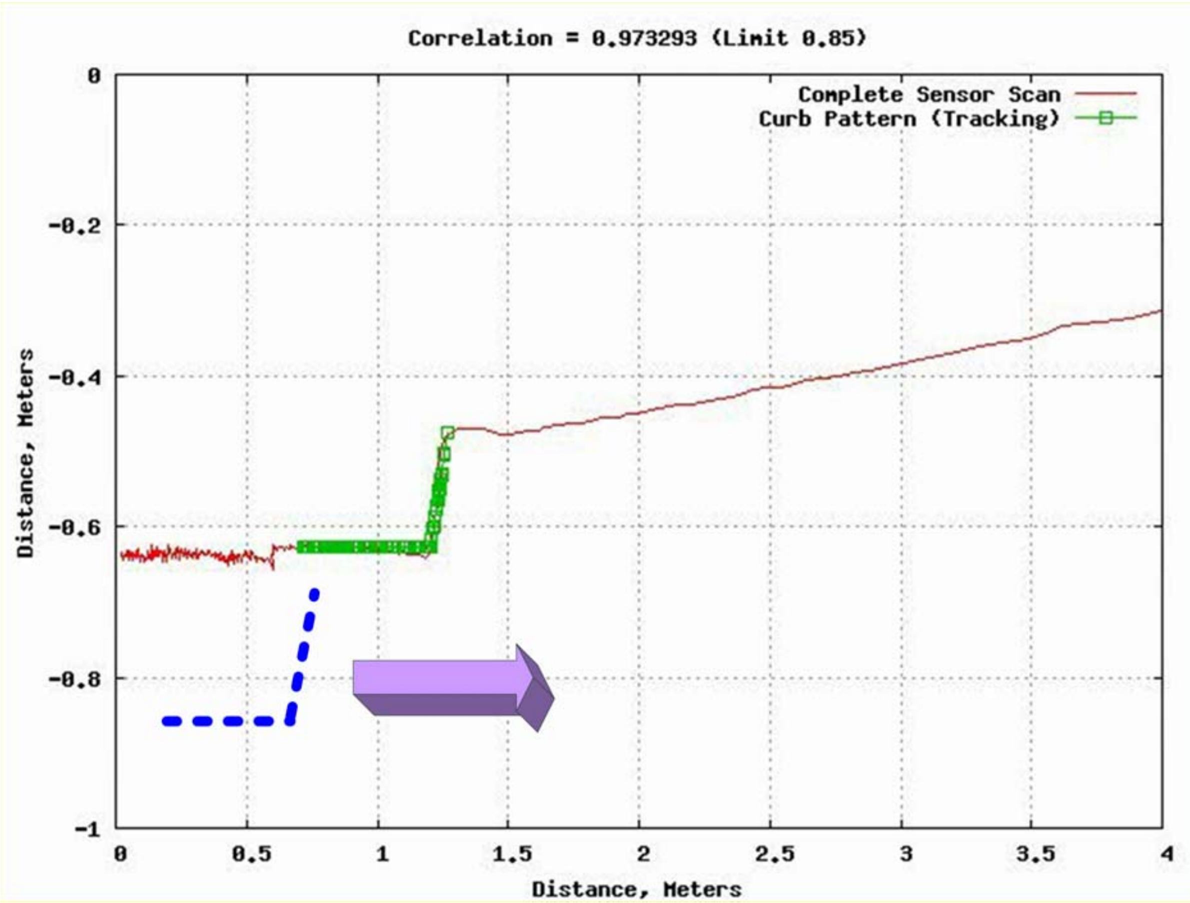

Figure 8. Cross-correlation example for a square curb using a curb profile captured with laser scanner data. In this example, the peak normalized cross-correlation value is 0.973, and occurs at a distance of approximately 1.2 meters from the right edge of the bus.

Using Equation 1 and a representative curb model (representative is discussed in more detail below), the cross-correlation (Equation 1) is performed starting the first element of the laser scan, producing $(f*g)_1$. This value is recorded. Metaphorically, the curb model is shifted to the right one index step, and $(f*g)_2$ is computed, and its value recorded. This process is repeated until the final cross-correlation, $(f*g)_l$ is computed. This produces an array of values for $(f*g)$.

The location of the curb with respect to the bus occurs at the location where $(f*g)_k$ reaches its maximum value. In other works, the curb is located at $x_k \mid (f*g)_k > (f*g)_i, i \in \{1,2,..l\}, i \neq k$.

Because of the mounting configuration of the laser scanner on the side of the bus, the resolution of the laser-scan as it senses the ground is variable. The resolution of the laser scanner along the ground decreases as the distance of the curb from the scanner increases. This phenomenon is illustrated in Figure 9 below. Because the geometry of the curb remains fixed, the decreased resolution of the laser scanner forces the reference curb model to be represented with a lower resolution as the cross-correlation proceeds away from the scanner.

The height of the laser scanner with respect to the road varies only due to variable passenger loads and due to road crowning. Because this variation is small, the distribution x_i associated with the laser scan can be pre-computed and stored in a database. To accommodate the lessening of resolution, the reference curb models (like those shown in Table 5) are modified so that the x_i are "spread out" so that the reference curb model x_i are spatially aligned with the laser sensor x_i. As the x_i are spread out, the corresponding f_i have to be modified to correspond to the spread out x_i. This "spreading" of x_i, however, reduces the number of elements in the cross-correlation process, producing less certain measurements as the distance between the bus and the curb increases.

It is important to note that the horizontal distribution of resolution shown in Figure 9 is shown for rays traced every 10 degrees. In actuality, the laser scanner produces a ray every 0.25 degrees, facilitating a relatively dense sensor reading even with a curb a few meters from the bus.

It is important to note that the curb geometry for a particular section of road can be measured *a priori*, enabling the curb reference model to be precisely matched with the physical geometry of the curb. Moreover, because the degradation in scanner resolution as a function of distance from the bus is deterministic, a series of reference curb geometric models can be computed *a priori* and used in real time.

The presence of the curb is indicated by a lower threshold on the maximum normalized correlation coefficient. For the curb geometry shown in Figure 8, the threshold for the normalized correlation coefficient for robust curb identification was 0.85. For the example in Figure 8, the maximum normalized cross-correlation coefficient was 0.973; that coefficient occurred at approximately 1.20 meters from the right side of the bus. The curb measurement reference is the lower "knee" in the curb model. In the frame in Figure 8, the knee occurs approximately 1.20 meters to the right of the bus.

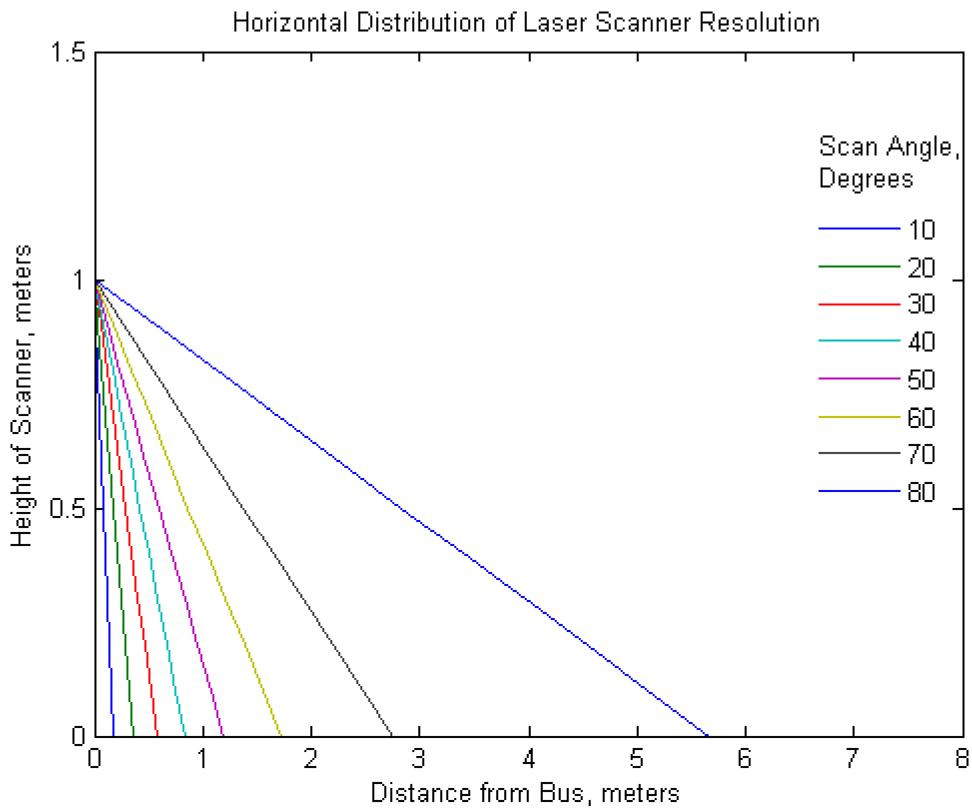

Figure 9. Horizontal distribution of the vertically mounted laser scanner used to detect the presence and location of curbs used to determine bus lateral position within a lane. The greater the distance from the curb, the lower the resolution of the laser scanner in the direction of the horizon.

Integration for Guidance.

Algorithmically, providing lane assistance using DGPS or using the integrated VPS-Laser scanner approach is quite similar. The lateral control algorithm, documented in [9.] and shown in Figure 10 below uses three feedback measurements to provide inputs to the steering controller: lateral offset, lateral velocity, and road curvature.

Each of these feedback measurements is available from the VPS-Laser scanner system. First, the determination of lateral position error is shown in Figure 11. Instead of the geospatial database used to locate, in global state plane coordinate, the position of lane boundaries, a database of desired "distance to the curb" values is used to determine lateral position error. This measurement is analogous to the distance to the lane boundary, and is used by the lateral control algorithm in precisely the same way.

Database queries to the standard IV Lab geospatial database are based on a GPS-derived global position. In the case of a "curb distance" database, queries are based on distance along the road traveled. The "curb distance" database will contain a curb reference profile and a desired distance from curb information. A query will return the local curb shape and a desired separation between curb and bus.

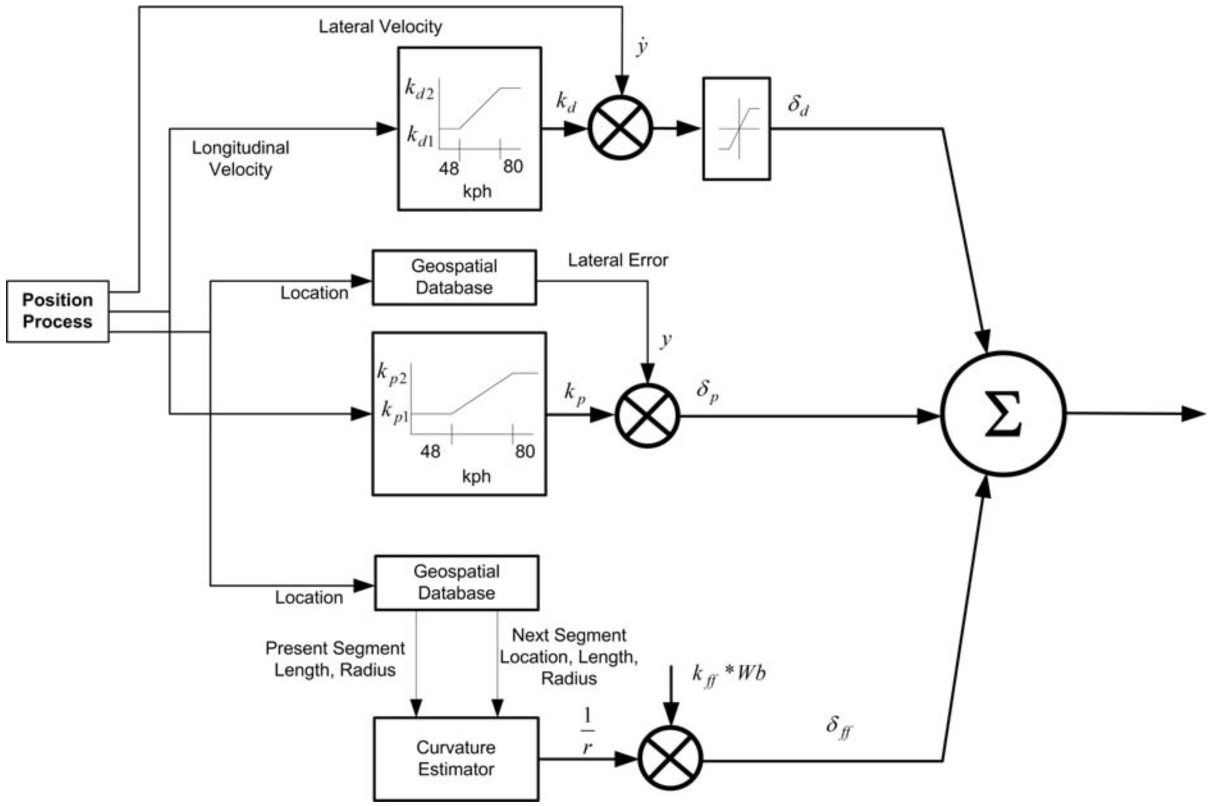

Figure 10. Lateral control algorithm for providing lateral lane assistance. Key feedback includes lateral position, lateral velocity, and road curvature. These three elements can be extracted from the VPS-Laser Scanner system, allowing the same control algorithm to be used for either DGPS- or VPS-based guidance.

Lateral velocity is derived in both the DGPS and VPS approaches. Using GPS, lateral velocity is derived from successive lateral error measures. Low pass filtering is used to mitigate the noise associated with estimating velocity from position measurements. With the laser-scanner approach, lateral velocity is determined by computing the rate at which the distance to the curb varies from the reference position. This computation allows the laterally control algorithm to work with the lateral velocity precisely with the laser scanner as it does under DGPS positioning.

To improve ride quality, to reduce feedback gains, and improve gain margin, the lateral controller used for lane assistance incorporates a feedforward term, with the feedfoward parameter road curvature. With the geospatial database, road curvature is a straightforward extraction from the road database. Road curvature is computed from the description of the "upcoming" road segment to be occupied by the vehicle. Because steering wheel position is proportional to the road curvature (the tighter the curve, the greater the steering wheel angle), upcoming road curvature provides a reference signal for the controller.

The VPS-Laser scanner approach does not provide a reference road curvature for vehicle guidance as the VPS system does not use the "standard" IV Lab geospatial database. However, because road curvature is proportional to steered wheel position (i.e., angle of the front wheels) and is dependent upon vehicle wheelbase, road curvature information can be estimated from steering wheel position.

The motor used to actuate the steering system on the research bus uses a Kollmorgen XT series MT306 motor with a 2048 line (8192 count per motor revolution) encoder. The motor drives the steering mechanism through a 3:1 reduction, producing 24,576 counts per steering wheel revolution. This is far more resolution than is needed to estimate road curvature.

The radius of curvature for roads requiring lane assistance tend to be large, allowing the steering system to operate in a fairly linear regime (i.e., the ratio $\frac{\partial Steering}{\partial Steered}$ remains nearly constant, where $\partial Steering$ is the change in steering wheel angle, and $\partial Steered$ is the change in steered or front wheel angle). Within this linear regime, the radius is proportional to the angular position of the steering wheel.

The desired distance from the curb map or database is generated by simply driving the roadways for which lane assistance is provided. A minimum of two runs is necessary; one to acquire a good curb profile model, and a second to record the optimum distance from bus to curb. To improve the fidelity by which the shape of the curb is captured, the first run is low speed with the bus in close proximity to the curb will be run. This utilizes the maximum available resolution of the vertically mounted laser scanner.

Data from the first run is post-processed to determine a reference curb model for each section of curb along the roadway. Once these models are available, a second run to determine the optimal distance from the curb is undertaken. This data is post-processed using the reference curb models resulting from the first run. The curb models are cross-correlated with the data collected on the second run to determine an optimal distance between bus and curb.

It is important to note at this stage that only the curb-correlator has been implemented. The VPS and Laser-based systems will be implemented in an ITS-Institute sponsored research program entitled, "Guidance Augmentation using VPS for transit Applications (VPS-BRT3)." The goal of this program is to implement the system described herein and demonstrate the system on a dedicated lane in Downtown Minneapolis on a dedicated bus lane in an area where GPS signals are unavailable.

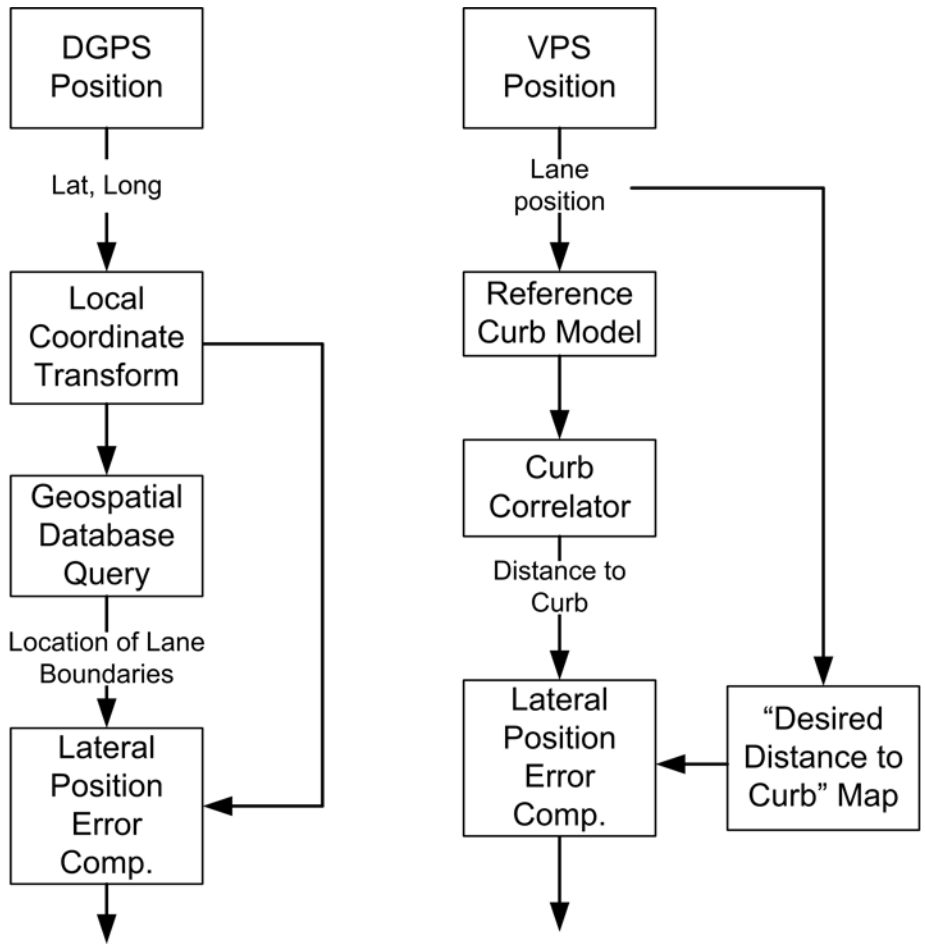

Figure 11. Lateral position error computation flow charts for DGPS-based lane assist (left) and VPS-based lane assist (right). Conceptually, the two approaches are similar. In practice, for a mixed mode guidance system (i.e., DGPS used where it is available, and VPS used where GPS is unavailable), the "Reference Curb Model" and "Desired Distance to Curb" maps can be embedded in the geospatial database which enables the DGPS-based lane assist approach. Because one feedback element in the steering algorithms described in [9.] (see Figure 10) is lateral error, both approaches provided the same feedback signal to the lateral controller.

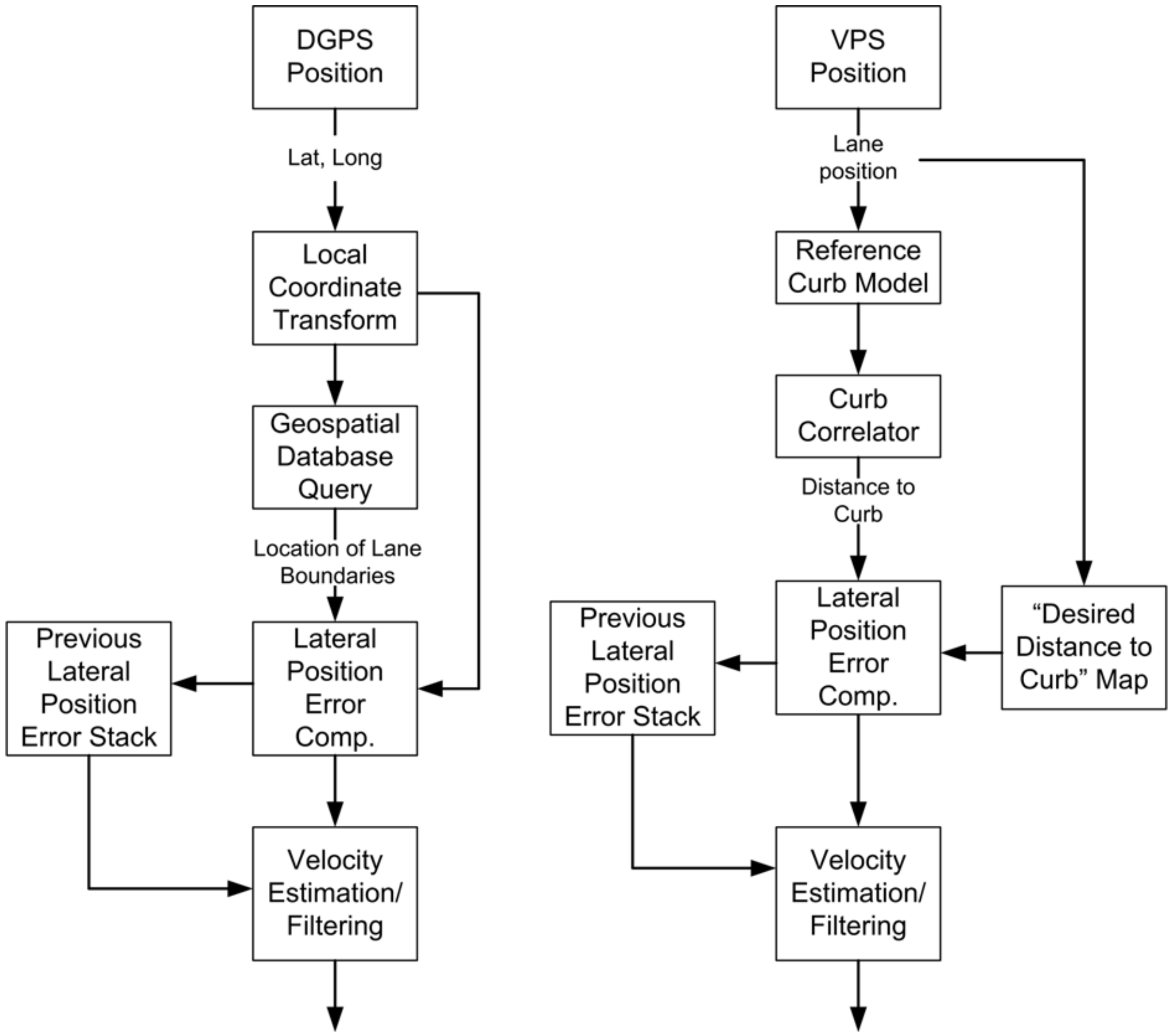

Figure 12. Lateral velocity error computation flow charts for DGPS-based lane assist (left) and VPS-based lane assist (right). Because a direct measurement of lateral velocity error is unavailable, lateral velocity is derived from lateral position. The "previous lateral position error stack" buffers past lateral position error; the "velocity estimation / filtering" block smooths the result of the differentiation process. Although lag is introduced in the estimation/filtering process, bus lateral dynamics are "slow," so this causes very few problems in the actual guidance process.

Chapter 3
Remote Sensing for Transit Applications.

Introduction.

The most difficult task while operating a bus on shoulders during rush hour is the process of avoiding collisions with traffic entering and crossing the shoulders from the entrance and the exit ramps, respectively. To assist the driver with traffic entering from entrance ramps, the Intelligent Vehicles Lab has developed a means to sense the position and speed of traffic on the entrance ramps using off-the-shelf automotive radar. The radar senses approaching vehicles, and wirelessly transmits this information to a bus operating on the shoulder. That information is displayed on an LCD screen in the bus, enabling the driver to "see" ramp traffic, and make decisions whether to maintain speed, accelerate, or decelerate to avoid a collision.

Figure 13 below shows the layout of a remote station site.

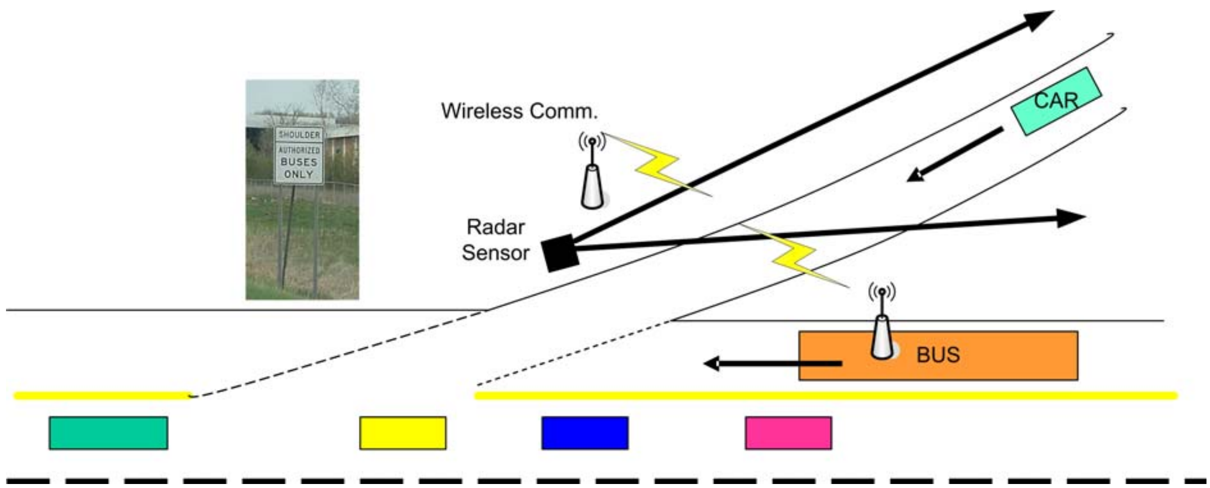

Figure 13. Layout of remote on-ramp sensing to support bus-only shoulder operations.

A radar sensor is placed adjacent to the on-ramp, and monitors traffic approaching the limited access highway. A small single-board computer processes location and speed information for vehicles traveling on the on-ramp. This information is broadcast wirelessly to the bus using a standard protocol (for demonstration, 802.1b; for deployment, perhaps DSRC.)

The on-board vehicle system carries a geospatial database which describes both the limited access road and the on-ramp. The radar processor converts radar target information in the radar coordinate frame to the local (state plane) coordinate frame.

Target information provided by the ramp radar is projected onto a display in the bus traveling on the shoulder. The bus driver is able to compare the relative position of the ramp targets to the position of his or her bus, and adjust speed to minimize the potential for conflict between the bus and the cars on the ramp.

Development.

The system shown in Figure 13 is based on the Intersection Decision Support work documented in [10.]. The system development consisted of two efforts:

1. Infrastructure development.

2. Vehicle development.

Infrastructure development. Infrastructure development was undertaken first. Minnesota Highway 252 north of I-94 and south of West River Road has served as a test and demonstration road for the bus technology program. Because a high accuracy map of highway 252 used for vehicle guidance exists, it was prudent to use this section of road. Moreover, traffic passing onto highway 252 from both eastbound and westbound highway 610 enter highway 252 at a common point, creating a conflict between buses using the shoulder and traffic entering the highway 252 traffic stream from eastbound highway 610.

Highways 610 and 252 are generally at the same elevation. However, to move traffic from highway 610 eastbound to highway 252 southbound, the exit ramp gains elevation after vehicles depart highway 610; after reaching peak elevation, the ramp drops traffic down to the elevation of highway 252.

This geographic location is shown in below in Figure 14.

Once a location was identified and approved, the next step was to create a high accuracy geospatial database of the area. This database serves two primary purposes:

1. Provides a means with which to determine the optimal placement of the radar for maximum coverage.

2. Provides a mechanism for visualizing the location and speed of radar targets on the ramp for the driver in the bus.

This high accuracy database was built and used to position the radar. Once optimal radar positions were determined, the locations were marked. On test days, portable radar stations were positioned in the right of way. Because of low power draw by the radar stations, batteries were used to power the radar along the side of the road. An example of a temporary radar station is shown in Figure 16.

Figure 14. Aerial view of the ramps leading from both eastbound and westbound highway 610 onto highway 252 in Brooklyn Center, MN. Note that both ramps gain elevation prior to the merge point, and then drop in elevation to highway 252 grade level. The distance separating the two directions of highway 610 traffic, combined with the large geographic area creates poor visibility conditions.

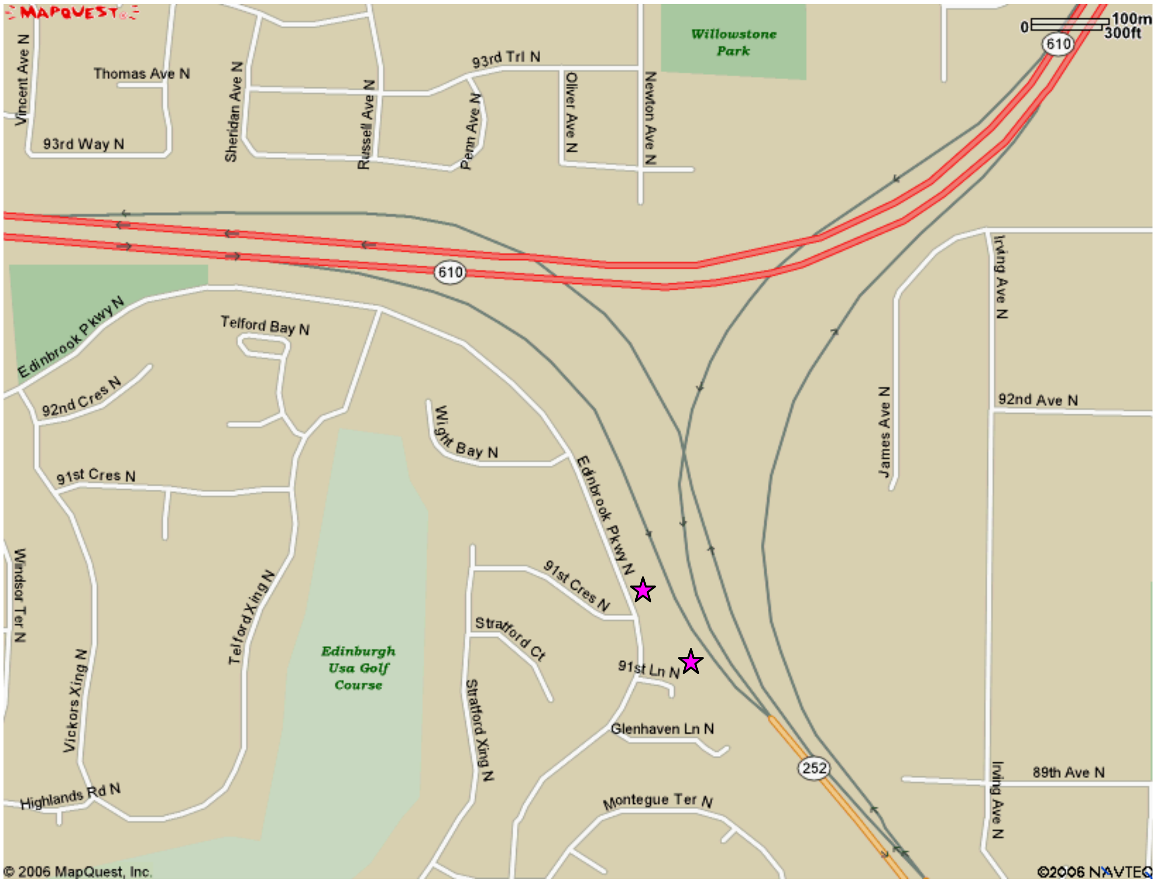

Figure 15. Location of equipment for remote sensing testing. The stars represent the location of the radar (approximately 400 feet apart). Batteries are used to power the radar for tests and demonstrations.

Figure 16. Picture of roadside radar sensor on entrance ramp from eastbound highway 610 to southbound highway 252. Omni-directional wireless antenna is on the top of the mast; the antenna provides direct communication to the bus. All graphic rendering is done on the bus processors.

*Vehicle development***.** Only slight modifications to the on-vehicle systems were needed to support the visualization of remote sensor data. First, a wireless access point was added to the Technobus to support the 802.11b communications from the roadside sensors. Second, the on-board database was modified to include the entrance ramp from eastbound highway 610. Third, the remote sensor data from the radar stations was included in the "virtual mirror" view to allow the driver to properly adjust the bus trajectory to avoid conflicts with traffic entering from the highway 610 entrance ramp.

Test results.

The system was tested on the on ramp on during the first week of June, 2006. Communications from the roadside sensors to the bus proved to be robust, and the on-board system was able to properly render the remote radar sensor data on the virtual mirror display, allowing the driver to adjust speed properly to avoid conflicts with entering traffic.

Video files recording the images seen by the bus driver using the system are found on the CD attached to this document.

Chapter 4
Conclusions and Recommendations.

*Conclusions***.** Described herein is a system designed to augment DGSP-based systems to provide lateral guidance/lane assistance for transit buses which operate within large geographic areas (i.e., downtown areas) where urban canyons and multi-path effects render DGPS-based approaches ineffective/unworkable. This augmentation approach integrates two discrete technologies to provide both lateral and longitudinal (i.e., along a known path) positioning. Position along the lane of travel is provided by VPS, which is explained in detail in [1.], and briefly herein in Chapter 2. Lateral position within a curb-bounded lane is determined using a laser scanner and a curb cross-sectional model. A model matching technique is introduced which allows a moving bus to detect the presence of a curb and a distance from the bus to the curb. An on-board database indicating a reference distance between bus and curb is compared to actual distance to provide an error signal for the lane assist system.

This augmentation approach facilitates the use of the existing lane assist system, thereby allowing the core lane system developed over the past six years to remain intact. This simplifies system implementation, and should accelerate system development.

Although the components needed to implement this system have been developed (to various levels) individually, they have not been integrated and demonstrated on real roads. This is the subject of a follow-on project (see "recommendations" below).

Also described (and demonstrated) in this work is an infrastructure-based radar approach to merge assistance for entrance ramps. Buses using bus-only shoulders experience a substantial number of conflicts per trip with vehicles entering the traffic stream from an entrance ramp. On roads where buses are prohibited from shoulder use, vehicles entering the moving lane of traffic can move unimpeded across the shoulder to merge with the adjacent lane of traffic. However, with bus-only shoulders, the merging vehicle and the bus on the shoulder often meet, creating a point of conflict. Because of grade separation, the bus driver often cannot see merging traffic, and cannot adjust his or her speed to accommodate the merging vehicle.

An infrastructure-mounted radar sensor (or sensors) properly located at an on-ramp and aimed at oncoming traffic can be used to assist a bus driver using shoulders to avoid conflicts. Radar data can be sent wirelessly to a moving bus (using 802.11, DSRC, or other means); radar target data can be presented on a display which can be used by a driver to adjust speed and avoid conflict. As shown herein, both the radar data and bus position data are rendered on an in-vehicle display. A driver is able to watch both the bus and the vehicle on the ramp, and make changes to bus speed to avoid a conflict when the vehicle on the ramp passes across the shoulder.

This system was implemented and demonstrated at the entrance to southbound Minnesota highway 252 from the eastbound lane of Minnesota highway 610.

*Recommendations***.** A follow-on project, the aim of which is to integrate the VPS and laser-sensor based guidance system has been funded, and is underway. This system will produce a DGPS-augmentation system capable of providing lane assistance in an urban area plagued by urban canyons and multi-path effects. The system will represent an implementation of the system described herein. The present project schedule calls for a demonstration of the system during the summer of 2008.

Remote sensing has been demonstrated using technology which has been proven in the field since 2004. The logical next step would be to deploy it in a field test at a location where buses regularly use shoulders during periods of high traffic congestion. The Intelligent Vehicles Lab and Minnesota Valley Transit have partnered to pursue a field test of lane assist technologies for Cedar Avenue. Because of the safety benefits offered by a merge assist system, remote sensing will be recommended as a technology to evaluate as part of the proposed Cedar Avenue field test.

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