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Bus Rapid Transit Technologies: Assisting Drivers Operating Buses on Road Shoulders

**Final Report
Volume 1**

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HUMAN CENTERED TECHNOLOGY TO ENHANCE SAFETY AND TECHNOLOGY

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Final Report Volume I

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Thanks are also due to Mn/DOT whose innovative use of DGPS allowed the IV Lab to use the Trimble Virtual Reference Station DGPS system during the development of the lane assist systems on the Technobus. Moreover, Mn/DOT provided traffic support during the “History Channel” filming, resulting in a safe environment under which to document the lane assist system.

Finally, Trimble has supported this research through its provision of an IV Lab mirror site to Mn/DOT’s VRS system. VRS provides high performance DGPS operation throughout the Twin Cities Metro area, allowing the IV Lab to demo its system anywhere in the Metro area.

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Executive Summary

The FTA has identified the concept of Bus Rapid Transit as a means to increase the efficiency of transit operations while maintaining transit's proven safety record. According to the FTA website www.fta.dot.gov, "BRT combines the quality of rail transit and the flexibility of buses. It can operate on exclusive transitways, HOV lanes, expressways, or ordinary streets. A BRT system combines *intelligent transportation systems* technology, priority for transit, cleaner and quieter vehicles, rapid and convenient fare collection, and integration with land use policy."

Because of the limited right-of-way available to build new (and possibly dedicated) lanes for BRT operations, the FTA has identified lane assist as an emerging technology which will enable deployment of BRT systems. The premise behind lane assist technology is to increase the safety of BRT vehicles as they operate in the more unique environments, such as narrow lanes. Lane assist technology will allow BRT vehicles to operate at the desired higher operating speeds while maintaining the safety of the passengers, BRT vehicle and the motoring public.

Metro Transit and Mn/DOT at the present time are cooperatively operating a BRT-like capability throughout the Twin Cities metro area. Buses operate in HOV lanes, on specially designated road shoulders (albeit at speeds significantly lower than limits posted for the adjacent highway), and are provided metered ramp by-pass capabilities in certain locations. At the present time, Metro Transit has 118 shoulder miles approved for BRT; approximately 15 to 20 miles of approved shoulder miles are added annually. These shoulders are considered by the FTA to be Lateral Guideways. These BRT like-capabilities, and others, provide the transit passenger faster, more efficient service when compared to traditional transit methods.

Although the bus-only-shoulder policy continues to be a very successful program, emerging driver assistive technology developed at the University of Minnesota can be used to solve problems associated with the bus only shoulder program. For instance, most of the shoulders on which transit buses operate are no more than 10 feet (3.05 m) wide; a transit bus measures 9.5 feet (2.9 m) across the rear view mirrors. These narrow lanes require that a driver maintain a lateral error of less than one-half foot (0.15 m) to avoid collisions. This is a difficult task under the best conditions, and degrades to impossible during conditions of bad weather, low visibility, high traffic congestion, etc.

In addition to maintaining the desired lane position, a driver also has to merge into traffic when the bus only shoulder area ends or a left exit is required. Although theoretically the bus has the right of way in such a situation, many times the driver has to "fight" for his or her position. This also adds considerable stress to an already difficult task.

The primary objective of this work was to equip a Metro Transit bus with driver assistive technology which will enable a driver of a Metro Transit bus to better guide a

transit bus on a narrow shoulder, especially under difficult conditions. This driver assistive technology was optimized for the bus driver. The technology associated with the primary objective will be aimed primarily at the lane keeping and forward collision avoidance tasks. This objective was met, and is the focus of Volume I.

The secondary objective is to investigate the Virtual Mirror as a technique for side collision warning and avoidance for transit applications. The virtual mirror has been implemented using existing geospatial database tools and DGPS as a range sensing device; however, for practical applications, LIDAR or similar ranging sensors will have to be used. A Virtual Mirror which utilizes LIDAR sensors was developed, and is the focus of Volume II.

The third objective will be to develop long term relationships with Metro Transit, the Federal Transit Administration, bus manufacturers, and technology providers to develop and implement strategies to improve transit operations. For instance, improving the ability of a bus driver to merge into and out of traffic is a high priority. Improved bus guidance technology will make bus only shoulders a viable alternative throughout the country. Progress towards meeting this objective has been made, but considerable effort will have to be expended to make lane assist technology ubiquitous throughout the transit industry.

Chapter 1. Introduction.

Background.

In 2000, discussions were held with Twin Cities Metro Transit to discuss operational problems and which problems are likely to be addressed or minimized by driver assistive technologies developed by the Intelligent Vehicles Lab (IV Lab). Through the course of these discussions, the Metro Transit practice of operating buses on “bus-only shoulders” was identified as a successful program, but not without its problems. Maintaining the proper lane position of a 9 ½ foot (2.9 m) wide bus in a 10 foot (3.05 m) wide lane is a difficult task in good weather, and nearly impossible in bad weather. A graphic illustration of the task the driver faces is provided in Picture 1 below.



Picture 1. Illustration of a 9 ½ foot (2.9 m) wide bus operating on a 10 foot (3.05 m) wide shoulder lane. Clearly, the margin for error is significantly less for the shoulder lane than it is for normal, 12-foot (3.7 m) wide lanes.

In bad weather, drivers have a difficult time determining the right boundary of the bus-only shoulder, and are therefore reluctant to use the shoulder because they fear dropping a wheel off of the pavement, and getting a bus stuck in the soft dirt adjacent to the shoulder. This is further complicated in snow events and in winter in general, where snow removal operations have left some shoulders snow covered and the right edge of the shoulder even more obscure.

It became apparent that that driver assistive technology developed by the IV Lab could address problems with bus-only shoulder operations. However, because the problems for the buses (lane guidance for narrow lanes) are sufficiently different for those for snowplows (vision enhancement in low to zero visibility conditions, see [1]), modifications and extrapolations to the snowplow technology would be required. Moreover, Metro Transit buses operate on shoulders primarily in urban and suburban areas as opposed to snowplows which experience low visibility in predominately rural areas. DGPS-based systems are more difficult to implement in urban and suburban areas because

1. the satellite constellation is more likely to be physically masked from the rover's antenna, and
2. because the identification of unused RF bandwidth on which DGPS correction signals can be broadcast is very difficult.

Bus-only shoulders have become a significant element of Metro Transit's operations. Presently, Metro Transit, with Mn/DOT support, operates approximately 200 miles of bus-only shoulder lanes in the Twin Cities area. Areas where bus-only shoulder operations are supported are shown in Figure 1 below.

There are a number of key advantages to operating buses on shoulders. First, infrastructure costs are low. It is far easier (and less expensive) to modify existing shoulders for bus-only operations than it is to construct new roadways. Second, because of the lack of congestion on the shoulders, Metro Transit is able to increase its percentage of on-time stops even during rush hour. Third, passengers on buses which use bus-only shoulder lanes perceive time savings roughly twice the actual time savings. In [2], an actual 8 minute time saving on a particular route was perceived to be a 15 minute time saving by the passengers. Passengers have become accustomed to the advantages of bus-only shoulder operation.

Rules of bus-only shoulder operation are relatively straightforward, and can be summarized as follows:

- Shoulder must be authorized with official signs for bus use.
- With traffic moving, bus speed is limited to 35 mph (56.3 kph) on shoulder, and may travel no more than 15 mph (24.1 kph) faster than adjacent traffic.
- If traffic is moving along at 35 mph (56.3 kph) or faster, buses must stay off shoulder.

- The decision to use the shoulder during periods of high congestion is solely that of the driver.

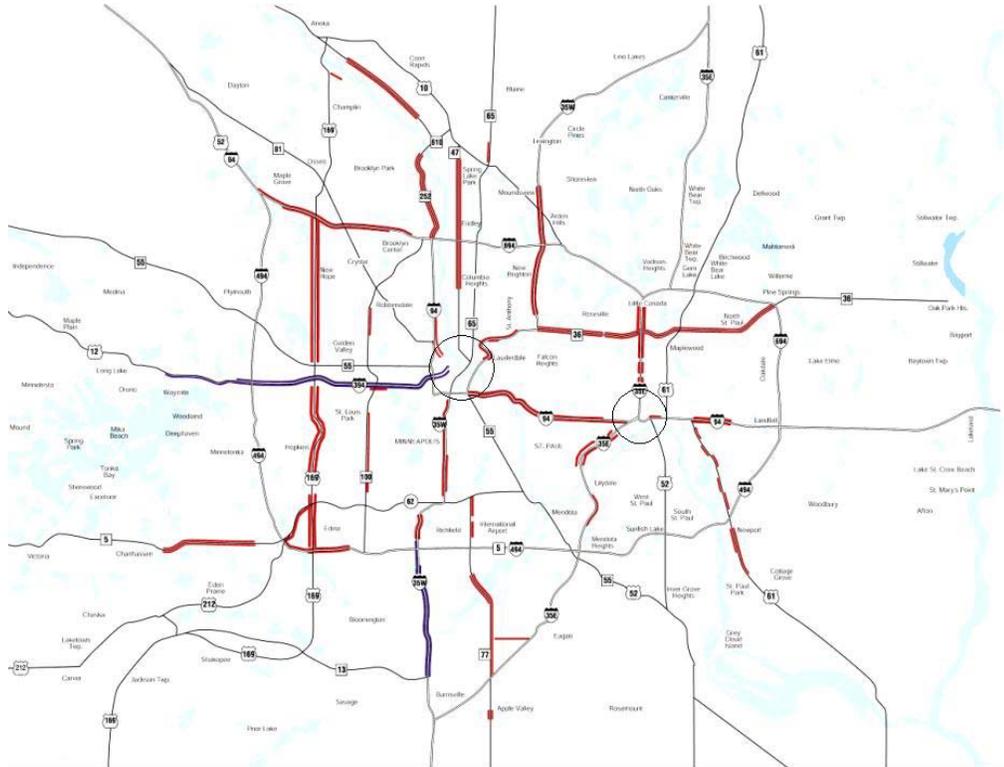


Figure 1. Bus only shoulder routes in the Twin Cities. Red lines denote bus only shoulder routes, and blue lines represent HOV lanes.

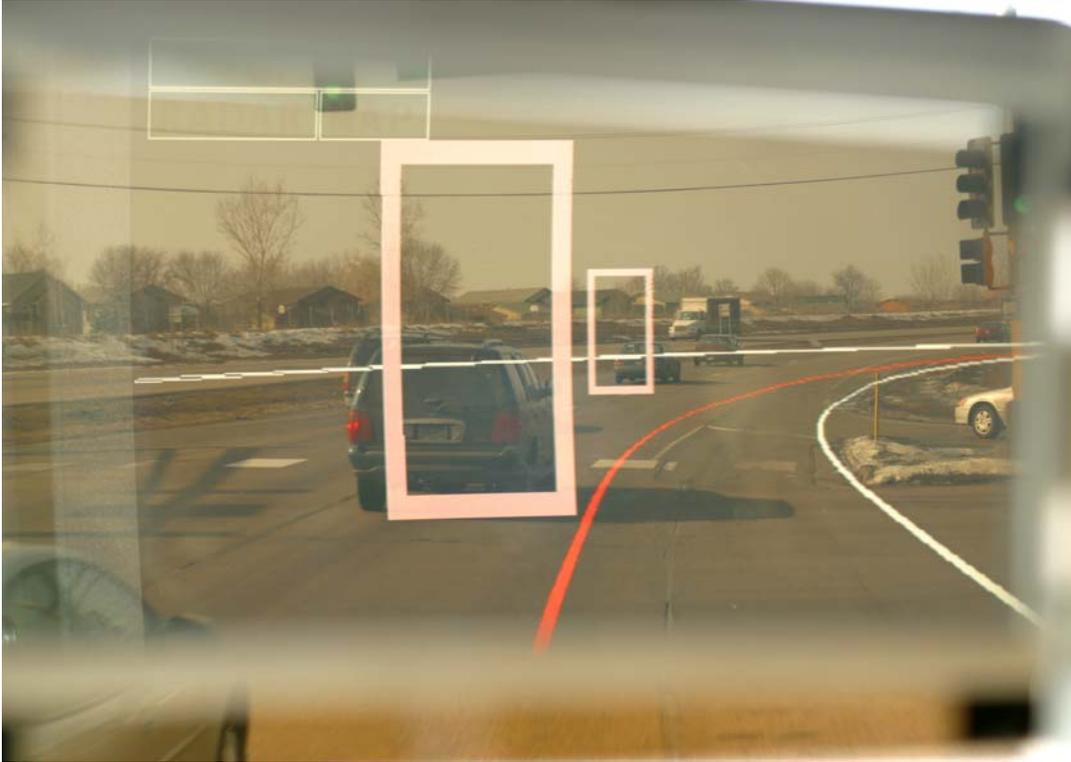
The decision to use the bus only shoulder is left to the driver; no driver is required to use the bus-only shoulder during periods of high congestion. However, passengers are aware that if the bus is not utilizing the shoulder lane, their destination will be reached later. Instances have been reported where passengers on buses not using the shoulder have used their cell phones to call the Metro Transit operations center, demanding that their bus driver move to the bus-only shoulder. Clearly, bus-only shoulder operations are a critical component of the Metro Transit system, both from the efficiency and customer satisfaction viewpoints.

To carry out the research, Metro Transit made available a forty-foot (12.2 m) Gillig bus, number 1972. Metro Transit named the bus “Technobus”, and wrapped it in a green graphic theme. The Technobus is shown in Picture 2 below, and is described in full detail in the subsequent chapters of this report.



Picture 2. Research Vehicle “Technobus” as supplied by Metro Transit. The Technobus is equipped with a lane assist system for narrow lane guidance, and forward, left, and right side collision avoidance systems.

The driver assistive system developed by the IV Lab uses three modalities to provide lane assist feedback to the driver. Visual information is presented to the driver via a Head Up Display (HUD) and a Virtual Mirror Display. The visual information presented to the driver via the HUD includes simple system status information, lane boundary position information, and forward target information. A representation of the information seen by a driver of the Technobus through the HUD is shown in Picture 3.



Picture 3. Photo of driver’s view through the HUD. Lines (white and red) indicate shoulder boundaries; red indicates that the bus is “out of lane” to the left side. (Simultaneously, the driver would “feel” the left side of the driver seat vibrate.) Square boxes indicate forward radar targets. If the target is fewer than 50 feet (15.25m) from the Technobus or within three seconds of a collision, the white (advisory) box would turn red. System status information is present in the upper left-hand corner.

Similar to the HUD display is the virtual mirror. Because of the tight quarters in which transit buses must travel, the (side mounted) rear view mirrors are kept close to the bus. However, close mounted mirrors create blind spots for the driver, making it difficult to merge into traffic.

To improve visibility on the sides of the Technobus, a LIDAR (Light Detection and Ranging) based Virtual Mirror is used. The Virtual Mirror is comprised of three components: a sensor, a processor, and a graphical display.

Picture 4 below illustrates the output of the Virtual Mirror System. Sensor information is processed by an on-board computer, and the output is presented to the driver graphically via a bright, flat LCD screen. The driver can choose between three views; illustrated here is the plan view option. The remaining views are “bird’s eye,” presenting data from an eyepoint behind and to the right of the bus, and the “virtual mirror,” which mimics the

view from an optical mirror (but with the added advantage of eliminating the optical blind spots.)



Picture 4. Picture of Virtual Mirror Display on the Technobus. In this plan view, the shoulder and adjacent lane of traffic are shown in grey, the top of the bus in white, and a radar or lidar detected obstacle in blue. The shoulder and lane information is provided by the on-board geospatial database.

Report Organization.

This report is divided into two volumes. Volume I provides design and performance documentation for the integrated driver assistive system. Comparatively, Volume I provides a less detailed view of the driver assistive system, whereas Volume II provides a detailed view of the technical details of the Virtual Mirror.

Volume II documents the development and performance of the Virtual Mirror side obstacle detection system designed for vehicles affected by poor coverage (i.e., blind spots) associated with conventional optical mirrors. The development of a side obstacle detection system was a significant undertaking which consumed approximately one-half of the project budget, and approximately one-half of the labor budget. Because of the magnitude of this effort, the development and performance of the Virtual Mirror obstacle detection system is documented in Volume II.

Project Task Description.

The work performed for this study consisted of 7 specific tasks, and is documented in two volumes. The results of Tasks 1-5, a portion of Task 6, and Task 7 are described in Volume I; the development and validation of the periphery obstacle detection system described in Task 6 is documented in Volume II. The description of the tasks below are taken from the original research proposal.

Task 1: Problem refinement. At the macroscopic level, it is relatively easy to postulate what problems are associated with operating a bus on the shoulder. However, it is prudent to ascertain the details and further refine the problem before attempting a technical solution. Therefore, the first task is to meet with drivers of all experience levels to determine details regarding the difficulties of driving a wide bus on a narrow shoulder. (These meetings may include further “ride-alongs” to get a better idea of the problems facing bus drivers.) Concurrently, select Metro drivers will be provided a demonstration of the current state of the art in driver assistive technologies as developed by the IV lab. Focus groups will then be held to determine a point from which initial work can begin.

Deliverable: A refined problem statement specifying project objectives and goals. Results of focus group discussions will be included.

Duration: 2 months.

Task 2: Optimal DGPS correction broadcast design. Driver assistive systems developed by the IV Lab use DGPS and high accuracy geospatial databases as the core technologies upon which all system functionalities are built. (These core technologies can be augmented with other guidance methods in situations where DGPS service is either impractical or unavailable.) DGPS uses fixed GPS base stations and a means to use wireless broadcast capabilities to sent appropriate corrections to a roving GPS receiver in real time.

In rural areas, where the competition for RF bandwidth is reasonable, frequencies in the 450 - 460 MHz band (i.e., the public safety pool) have been used by the IV lab to deliver corrections to roving GPS receivers. However, in urban areas, the public radio safety pool is typically consumed, leaving a limited number of options for the provision of DGPS corrections.

At the time the proposal was written, real time corrections were provided to the roving GPS receiver only from a single, dedicated base station. Using a single, fixed GPS base station required that the roving GPS receiver remain within 9-12 miles (15-20 km) (depending on conditions) of a base station to maintain the accuracy needed for driver assistive system use. If the distance to the base station is to be greater than the 9-12 miles (15-20 km), another base station would be needed to provide the corrections.

Just after the workplan was approved, Trimble introduced and Mn/DOT purchased a Trimble Virtual Reference Station (VRS) system. With VRS, a network of base stations separated by up to 60 miles (100 km) is connected to a central server. In real time, raw satellite observables are sent from the base stations to the central server, providing the information needed to provide optimized corrections for any carrier phase GPS receiver within the perimeter established by the outermost VRS GPS base stations. VRS functions via duplex communications between the rover and the VRS server. The roving receiver connects to the VRS server, and provides a coarse position to the server. The VRS server uses this coarse position to compute, at a 1 Hz rate, a least squares weighted optimized correction for the rover at that coarse position. This system will be evaluated as part of this task.

Deliverable: A selected method with which to provide GPS corrections.

Duration: Two months.

Task 3: Infrastructure Build. In this task, the infrastructure necessary to provide lateral lane keeping will be built and installed. The infrastructure includes the procurement and installation of the GPS receiver used as a base station, the procurement and installation of the chosen method of providing GPS corrections, and the collection of the geospatial data and the processing of that data which is used for lane keeping and forward collision avoidance.

Deliverable: A physical means with which to provide DGPS corrections along the selected corridor, and a geospatial database with needed accuracy.

Duration: Four Months

Task 4: Bus Mechanics and Dynamics. The research team has considerable experience with heavy and specialty vehicles (i.e., semi tractor-trailers, snowplows, etc.), but limited experience with large transit vehicles. Metro Transit buses are rear engine, sometimes articulated, which leads to steering systems and mass distributions different than those on our other research vehicles. For this task, Metro Transit will identify a bus

which will be used for the work proposed herein. University researchers will study mechanical components (primarily steering gear) so that steering actuation can be provided and study cabin layout (for mounting of the driver assistive displays and requisite computer and sensor hardware). Moreover, University researchers will investigate bus lateral and longitudinal dynamic capabilities (necessary because of the rear engine configuration and the change of handling properties between the loaded and unloaded conditions).

Deliverable: Documents from which a steering actuation system can be designed and a mathematical model of the bus lateral and longitudinal dynamics to be used in Task 5 below.

Duration: Four months

Task 5: Driver Assistive System for Vehicle Guidance. In this task, researchers will install the mechanical, electronic, sensor, actuator, and display systems necessary to provide lateral driver assistance to a bus driver operating a standard transit bus which is wider than an average vehicle on a narrow shoulder. This technology will be adapted from the system presently under development for the SAFELOW program and optimized for transit buses. This application specific optimization is required because the bus differs from a snowplow in both driver cabin layout and operational details. Problems identified in task 1 above will serve as a performance goal for this task.

The technology to be included in the longitudinal driver assistive system include a HUD, a DGPS system, an Inertial Measurement Unit (IMU), forward looking radar, power supplies, computers, steering actuation and amplification, and other peripheral equipment required to provide lane keeping driver assistance. Researchers and Metro Transit will cooperate to determine suitable locations where development can be performed.

The HUD will be used to provide the driver assistance when visibility conditions are poor and it is difficult to identify both lane boundaries and obstacles. Modifications will be made to the standard HUD model as needed to provide a driver additional information if required. An active steering wheel will provide haptic feedback to provide additional cues to the driver; under general operating conditions, the active steering wheel may act as the primary driver interface.

Deliverable: A lateral guidance driver assistive system optimized for narrow bus only shoulders and supporting design documents.

Duration: Seven months.

Task 6: Collision Avoidance for Transit Applications Task 6 represents the higher risk component of the proposed research. Task 6 represents an adaptation and optimization of technology previously developed for snowplows. Task 6 includes longitudinal collision avoidance under low visibility conditions in the sense that a

forward looking radar is used to detect objects in the forward path of the bus, and the HUD is used to provide an iconic representation from which the driver can estimate the range, range rate, and azimuth angle to radar detected obstacles. However, avoiding collisions around the periphery of the vehicle has not yet been investigated. This is the primary focus of this task. Two particular components of this collision avoidance problem will be considered; sensing and the driver interface for both forward and side collision avoidance.

Deliverables: A report documenting the development of the virtual mirror obstacle detection system. A prototype of the virtual mirror will be installed on the bus.

Duration: Eight months.

Task 7: Develop Partnerships. Proposed herein represents a one year effort to initiate a BRT program in Minnesota. The focus is to leverage previous driver assistive technology development at the University as a means to demonstrate improved bus on shoulder performance and to develop innovative collision avoidance systems specifically for buses.

Additionally, University personnel will work closely with Metro Transit to develop a mutually beneficial relationship with FTA and secure additional funding to support a multi-year BRT initiative in Minnesota. One such program might involve the application of driver assistive technology to exclusive busways. Infrastructure and right of way costs might be significantly reduced through the use of driver assistive technology which allows for 10 foot instead of 12 foot wide dedicated lanes.

Deliverable: A commitment from FTA to support BRT activities in the Twin Cities, and an effort to form a partnership to develop bus specific side looking radar.

Duration: Ten months.

Chapter 2. Problem Refinement

The purpose of the problem refinement task was to meet with Metro Transit personnel, specifically drivers, trainers, and management, to determine what specific problems to address and approaches to take as part of this research effort.

The effort to deal with trainers and drivers began with a presentation at a meeting of driver representatives at the Metro Transit Heywood facility on 04 January 2001. At this meeting, a presentation describing IV Lab driver assistive systems was made to the driver representatives. Based on the positive response from the driver representatives, a live demonstration of the technology was arranged for drivers on 13 February 2001 at the University of Minnesota Rosemont Research Station. The Rosemont Research Station was used at that time for a series of human factors experiments involving the SAFEFLOW research vehicle equipped with driver assistive technology. Using the SAFEFLOW allowed Metro Transit Trainers an opportunity to experience the technology first hand. Response from that demo was positive as well.

A number of suggestions of where to take the program were solicited at that meeting. First, the trainers confirmed that lane assistance for shoulder operations was a priority. Second, lane changing is also a very stressful task for the drivers, because of the types of mirrors used on buses. We were able to demonstrate an early prototype of the virtual mirror system, and reaction was enthusiastic. Given an emphasis on right vs. left virtual mirror application, the trainers placed a higher priority on the left side of the bus because for most shoulder applications, they typically have to move from an empty shoulder to a crowded lane to their left.

Other suggestions included a right-side Virtual Mirror to complement the left side sensing. The right side sensor should not only detect vehicles, but also people on that side of the bus. In fact, it was made clear that the detection of persons alongside the right side of the bus is a greater priority than sensing other vehicles on the right.

The other technology the driving instructors asked to see was infrared sensing. During the evening hours, drivers have a very difficult time determining whether a passenger is waiting at a bus stop to ride a bus. If the driver is unsure whether a passenger is waiting, she has to stop the bus and check. This uncertainty can lead to increased dwell times and route inefficiencies. Infrared sensing would better allow the drivers to determine the presence of passengers, and allow them to better maintain route schedules. (Infrared sensing technology for a driver assistive system is the focus of a separate IV Lab research project.)

Based on feedback from the drivers, the project objectives became:

- Demonstrate a lane assist system to support bus-only shoulder use during all weather conditions, including snow, rain, sleet, etc.
- Demonstrate a side collision warning system to assist a driver with merging operations on the left and right sides, and passenger detection on the right side.

These objectives were met, and the system installed in the Technobus at the conclusion of the project provided narrow lane guidance assistance (including forward collision warnings), left side collision avoidance system optimized for the detection of vehicles, and a right side collision avoidance sensor optimized for the detection and tracking of pedestrians on the right side of the bus.

Chapter 3. Optimal DGPS Correction Broadcast Design.

Provision of GPS corrections to a roving receiver requires two basic components: the data used for that correction and a means to transmit that correction data to the roving receiver. Both components are addressed in this chapter.

Application of convention RTK corrections.

At the time the project was proposed, the only commercially available option for providing GPS corrections was from a single base station. Using a single base station for carrier phase corrections limits the baseline or distance a roving receiver can be from the base station and maintain the accuracy needed for vehicle guidance.

On a more limited scale, the Intelligent Vehicles Lab had implemented a GPS correction scheme on Minnesota Trunk Highway 7 between Hutchinson and I-494 in the Twin Cities. This system uses three base stations, a single broadcast frequency, and time “slicing” of the correction broadcast from each of the three base stations. This allowed a relatively large geographic area to be covered with a single broadcast frequency. This method is illustrated below in Figure 2 and Figure 3.

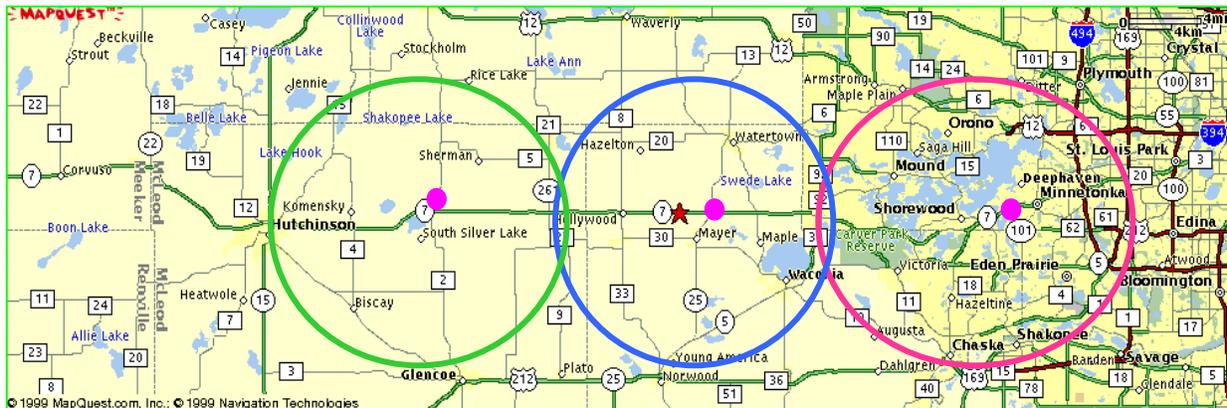


Figure 2. Highway 7 corridor showing locations of GPS base stations. Green is Silver Lake, blue is Mayer, and red is Chanhassen.

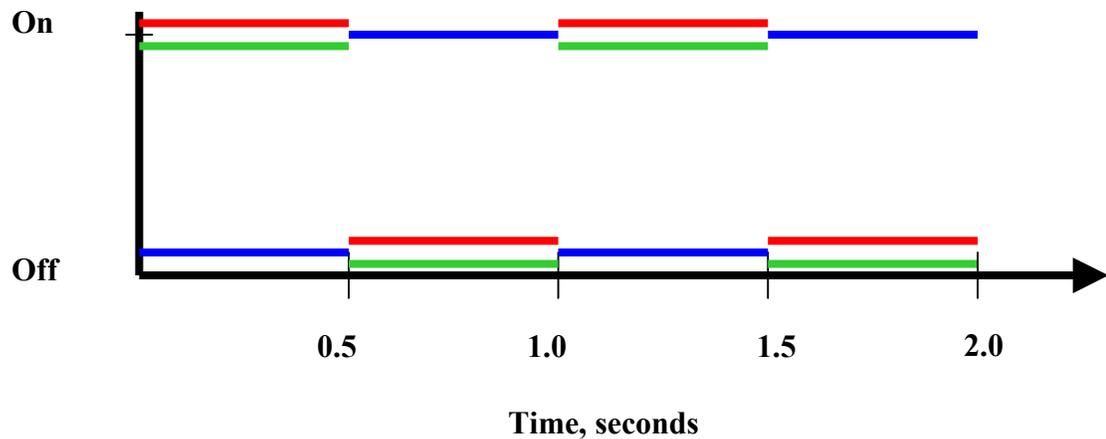


Figure 3. Timing of GPS base stations along Highway 7. Eastern and western stations are active while center is quiet, and *vice versa*.

Although this time slicing method worked well for Highway 7, it is designed only for a rectilinear application. To provide correction data over a “two-dimensional” area, GPS base stations would need to be located in a 2 dimensional grid throughout the Twin Cities Metro Area. Creating this grid of GPS base stations would be a straightforward process; however, providing the appropriate correction data from each of the base stations to the roving receiver using a wireless communication method is the prime difficulty with this approach.

To implement conventional RTK corrections over a “two dimensional” area, the extrapolation of the method used on Highway 7 becomes substantially more complex. Given the available bandwidth on the public safety pool channels (25KHz represents a wide channel) and the structure of the CMR (Compact Measurement Record) correction message, at least one additional channel would also be needed to support these broadcasts. The channel distribution to cover a two dimensional space with GPS corrections can be illustrated in Figure 4 below.

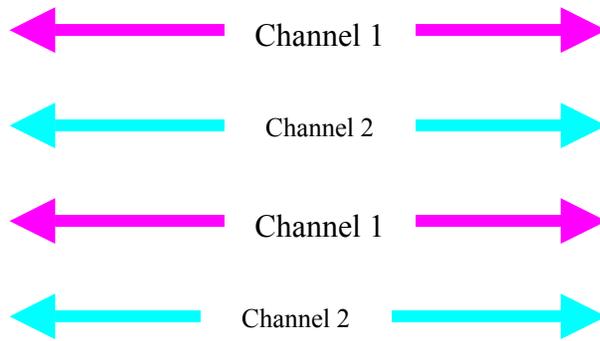


Figure 4. Spatial distribution of channel access for provision of GPS corrections over a two dimensional area. Each channel needs a specific timing algorithm to avoid cross talk between base stations.

Implementation of this approach is possible, but cumbersome. First, it is very sensitive to timing errors. Second, it is difficult to find an open channel in the public safety pool which covers an entire metropolitan area; it is even more difficult to locate two channels. Third, a dual channel RF Modem would be needed to accept corrections from each of the two channels. This two-channel RF Modem would require external control based on GPS time to synchronize signal reception with the timing of the GPS broadcasts. This adds to the complexity of the system.

Clearly, the implementation of a conventional RTK GPS correction methodology over a wide area is a complicated process from the wireless communication point of view. Moreover, because of the relationship between position accuracy and baseline, a grid of base stations with station spacing of approximately 15 miles (24 km) is needed. This number of base stations increases the cost of the infrastructure needed to support DGPS applications.

Fortunately, shortly after the project workplan had been approved, Trimble introduced its Virtual Reference Station approach to the provision of DGPS corrections over a wide geographic area. A schematic of this approach is shown Figure 5 below.

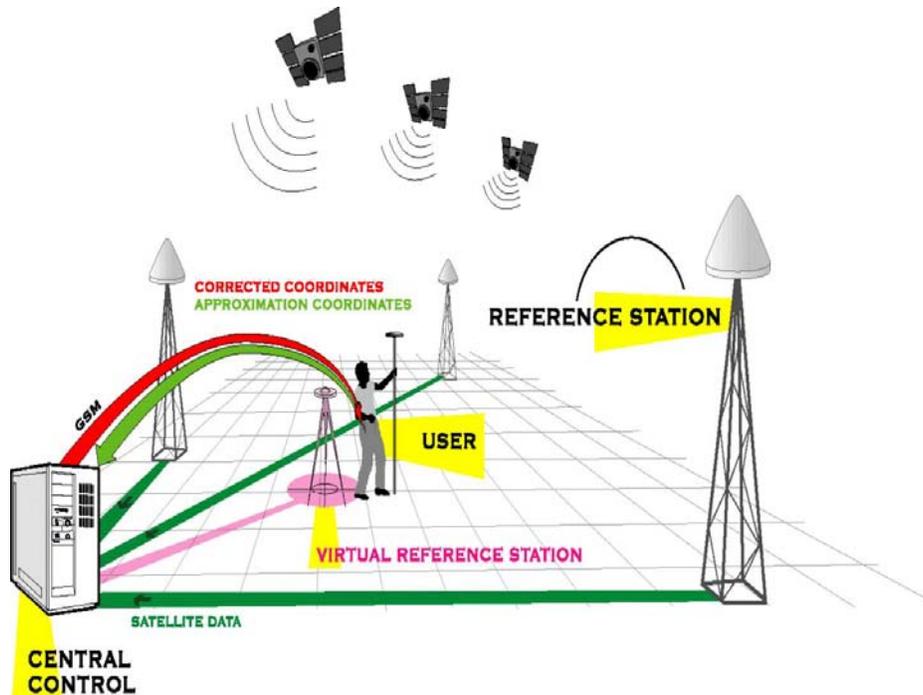


Figure 5. Schematic of the Trimble Virtual Reference Station. Raw observables from a grid of GPS base stations are continuously sent to a central server. The rover makes a connection to the server, and provides its coarse position. The server responds, and provides an optimized (using a least squares approach) correction for that specific location. (Trimble Graphic.)

The VRS system offers a number of advantages over a conventional RTK system. First, because of the least squares approach simultaneously using multiple base stations, the spacing of base stations can be increased significantly. Base station separation of up to 60 miles (100 km) has been demonstrated, offering positioning performance equivalent to that of conventional RTK system at a 10 mile (16 km) baseline. Second, issues associated with the timing and frequency of broadcast of corrections from a network of conventional RTK stations are eliminated because the data server continuously provides a correction to a specific rover at 1 Hz. (However, new issues arise with this approach. These are discussed below).

Much to our benefit, Mn/DOT purchased from Trimble a VRS system and has deployed it in the Twin Cities Metropolitan area. Its coverage area is illustrated in Figure 6 below. Using either CDPD or Cell Phone to receive corrections, it is theoretically possible to receive DGPS corrections from the VRS system anywhere within the Mn/Road-Hollywood-LeSuer-Red Wing-Chisago City polygon.

VRS works via duplex communications. When a GPS receiver is first “connected” to VRS, it provides the VRS server with its coarse (i.e., uncorrected) position. From that coarse position, the VRS system computes a least squares optimal correction for that coarse position, and then broadcasts GPS corrections to that rover at a 1 Hz data rate.

While connected to the VRS server, if a rover moves more than 1 mile (1.6 km) from its original position, the VRS server updates the rover position, and provides corrections for that new position.

The VRS server can handle multiple rovers; the maximum number of rovers is dependent upon the performance capabilities of the server on which the VRS runs and the number of Ethernet ports available through the firewall.

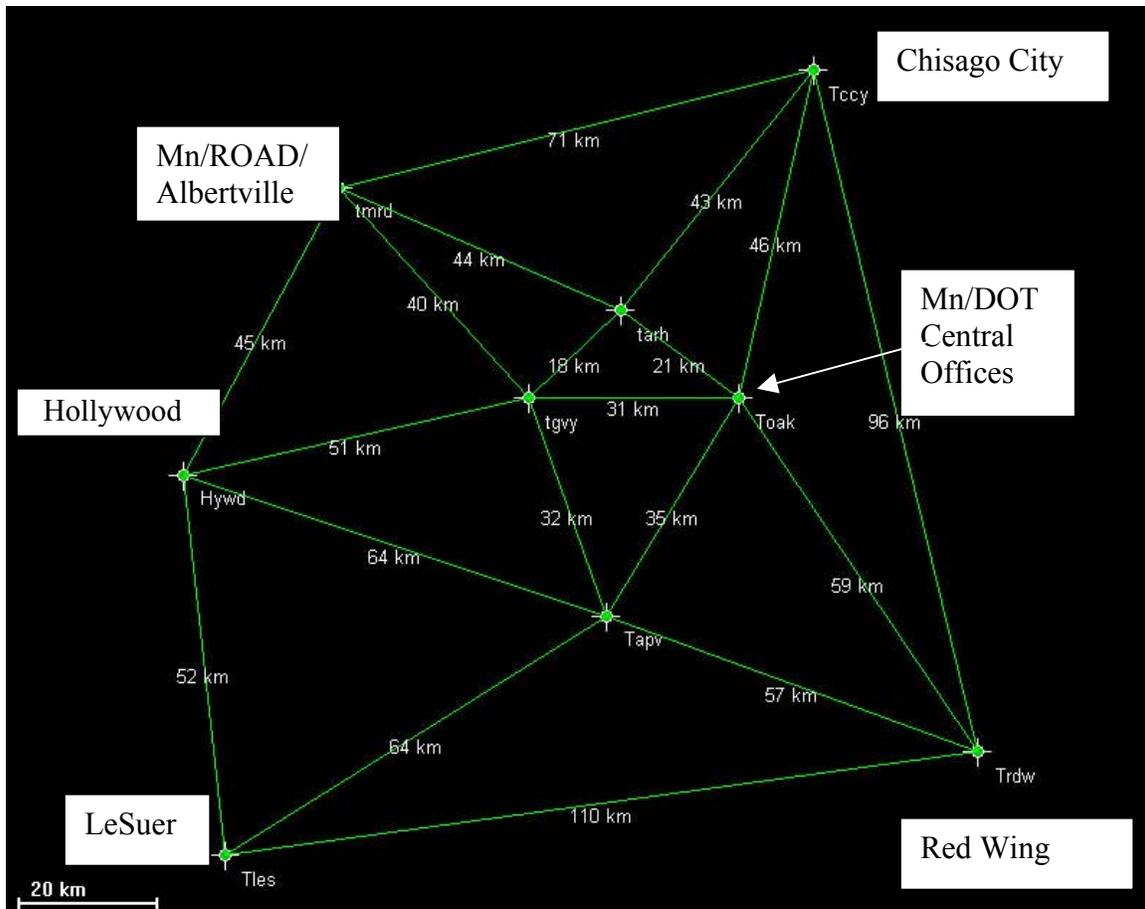


Figure 6. Trimble VRS coverage in Minnesota. VRS corrections are available for the area within the polygon above. Whether corrections can be provided depends on digital cell phone and CDPD modem coverage.

GPS performance (and specifically accuracy) directly affects the performance of any GPS based driver assistive system. Before such a system can be deployed, the accuracy of the GPS system must be quantified.

In [3], the dynamic accuracy of a number of GPS receivers, base stations, and the VRS system as measured against ground truth are documented. Position solution accuracies for

both RTK and VRS for both short and long baselines are provided in Table 1 and Table 2 below.

Table 1. Position error for SHORT baseline VRS.

| SPEED, MPH (KPH) | Number Images | Mean error, in (cm) | Standard Deviation, in (cm) | Average Latency, mSec |
|---------------------------------|--------------------------|------------------------------------|--|--------------------------------------|
| 10 (16) | 95 | 3.4 (8.6) | 3.5 (8.8) | 50.0 |
| 20 (32) | 59 | 3.5 (8.8) | 1.1 (2.9) | 40.2 |
| 30(48) | 20 | 4.1 (10.4) | 4.7 (12.0) | 43.6 |

Table 2. Position error for LONG baseline VRS.

| SPEED, MPH (KPH) | Number Images | Mean error, in (cm) | Standard Deviation, in (cm) | Average Latency, mSec |
|---------------------------------|--------------------------|------------------------------------|--|--------------------------------------|
| 10 (16) | 93 | 3.7 (9.4) | 3.5 (8.9) | 45.6 |
| 20 (32) | 58 | 2.8 (7.1) | 1.8 (4.6) | 48.2 |
| 30(48) | 18 | 2.9 (7.3) | 1.8 (4.5) | 43.6 |

Test results clearly show good DGPS performance.

To provide a second test, the IV Lab installed a GPS base station on the Mechanical Engineering building on the University of Minnesota Minneapolis campus. The performance of the Trimble ms750 using VRS corrections was tested (subjectively) against the performance of the ms750 using the Mechanical Engineering base station. (The baseline from the ME building varied between 10 (16 km) and 13 miles (20.9 km); the VRS baseline varied from 0 to 3 miles (0 to 4.8 km). Accuracy performance of the two systems was indistinguishable; both systems provided reliable, repeatable, accurate solutions under a wide variety of conditions.

Broadcast of DGPS corrections.

Because of the dearth of available frequencies in the public safety pool upon which DGPS corrections could be broadcast, the available choices were limited to RF transmission on consumer frequencies (900 MHz, 2.4 GHz), CDPD modems (CDPD: Cellular Digital Packet Data. A data transmission technology used to send data to and from cellular devices. CDPD uses cellular channels in the 800-900 MHz range and transmits data in packets. CDPD can achieve data transfer rates up to 19.2 Kbps.), or digital cell phones capable of wireless modem operation.

Wireless broadcasts on the consumer frequencies were ruled out early. The IV Lab uses RF modems which operate in this frequency band when providing demonstrations at remote locations where other methods of correction broadcast are unavailable. The main

drawback to these systems is that they offer poor maximum range. Typically, using 1 Watt radios with antennae providing 3 db of gain, the maximum range for reliable data transmissions (where “reliable” by our definition is that 90% of GPS corrections which are broadcast are received) is approximately one mile. This range is insufficient for vehicle applications which cover a large geographical area.

The 90% definition would, on average, allow 1 CMR message be dropped for every 10 sent (or every 10 seconds). Dual frequency, carrier phase DGPS can maintain a “fix” solution if the correction age is less than 5 seconds. The 90% mean reception rate ensures that the probability that a correction will be received at least once every five seconds is 99.99%.

This leaves two alternatives. CDPD broadcast of corrections was initially considered, for two reasons. First, the Mn/DOT VRS system was originally configured for CDPD based VRS corrections. This provided a straightforward implementation of the VRS system for the bus-only shoulder application. Second, the acquisition of a CDPD modem is a simple, inexpensive proposition (\$500 for an Airlink CDPD modem with external antenna), and CDPD airtime is relatively inexpensive (AT&T provided unlimited data for \$54.95 per month). Moreover, the University of Minnesota ITS Laboratory uses CDPD technology to provide continuous data from remote sensing sites with excellent results. Preliminary indications were that the provision of corrections using CDPD technology would be successful.

However, in practice, the CDPD approach was found to be problematic in the Twin Cities for two reasons:

1. A large number of coverage “holes” can be located in the Twin Cities Metro Area. This results in a loss of GPS corrections, and therefore DGPS accuracy decreases to a level unacceptable for lane assistance.
2. VRS is presently configured to communicate via the TCP/IP protocol. This protocol is designed such that if a packet is lost, the packet is rebroadcast until it is received (and acknowledged). In the event that a CDPD coverage hole is encountered, undelivered packets stack up until the connection is re-established. Given the bandwidth limitations of CDPD, this stack may never be cleared.

The ability of a DGPS system to deliver high accuracy is dependent upon the age of the GPS correction. With the TCP/IP approach, if packets are stacked up, the correction messages may not “catch up.”

Two corridors were used for the development of the driver assistive system described in this report. The first corridor, mostly used for system development, was the University of Minnesota Transitway which connects the Minneapolis East Bank campus with the St. Paul campus. This transitway, approximately 2.8 miles (4.5 km) in length, was covered

by CDPD only over the eastern third of the corridor. Results of coverage are shown in Figure 7 below.

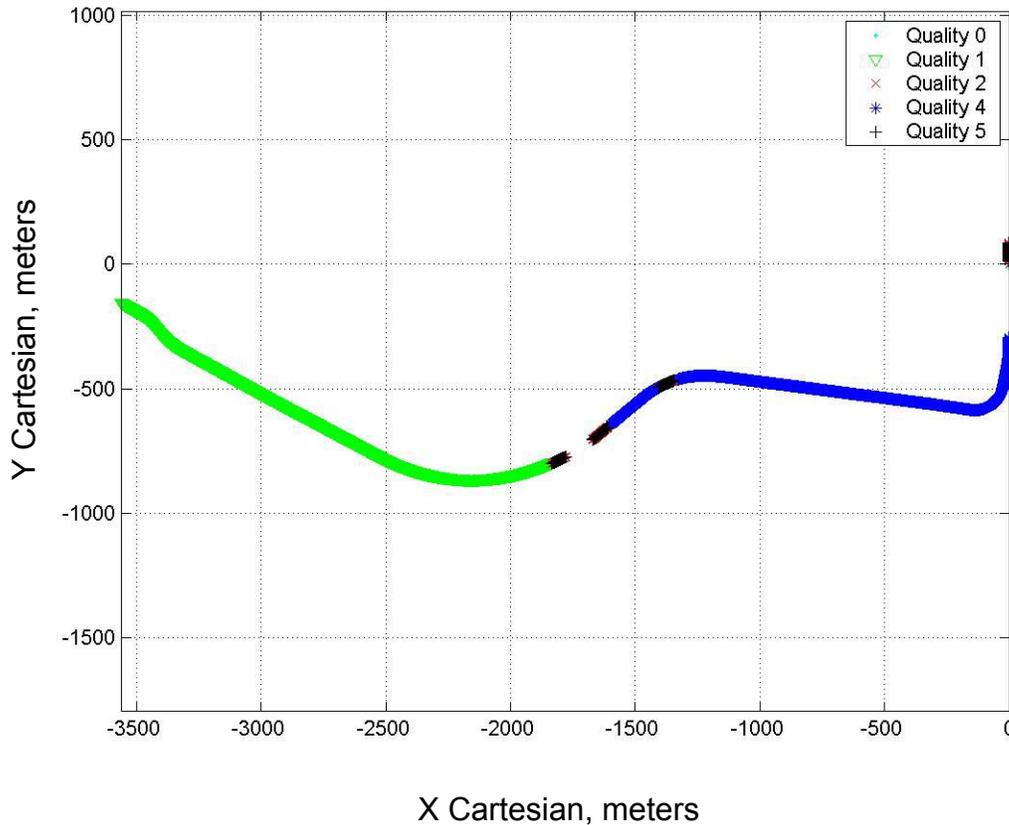


Figure 7. Plot showing coverage areas of CDPD modem on the University Transitway. Blue represents where CDPD coverage was available, and green represents the area where no CDPD coverage exists. Gaps in the data are the result of the GPS satellites being physically masked from the antenna. At (-1700 meters East, -750 meters North), GPS satellites are blocked by the Highway 280 overpass. At (0 meters East, -250 meters North), GPS satellites are blocked by heavy foliage. Black represents the region where CDPD coverage exists, but where the GPS receiver has not yet reacquired a solution after losing satellite lock.

In the event that the experience on the transitway was an anomaly, CDPD was used at a second location. This location was the Trunk Highway 252 corridor, the first corridor used by Metro transit for bus-only shoulder use. (This bus only shoulder lane was also the site for the human factors study in an FTA-Metro Transit sponsored project titled, “Technical requirements for Lane Assist systems.”) Here, CDPD modems were found to

suffer from the same lack of coverage as on the University transitway. Figure 8 below illustrates the CDPD coverage on Trunk Highway 252.

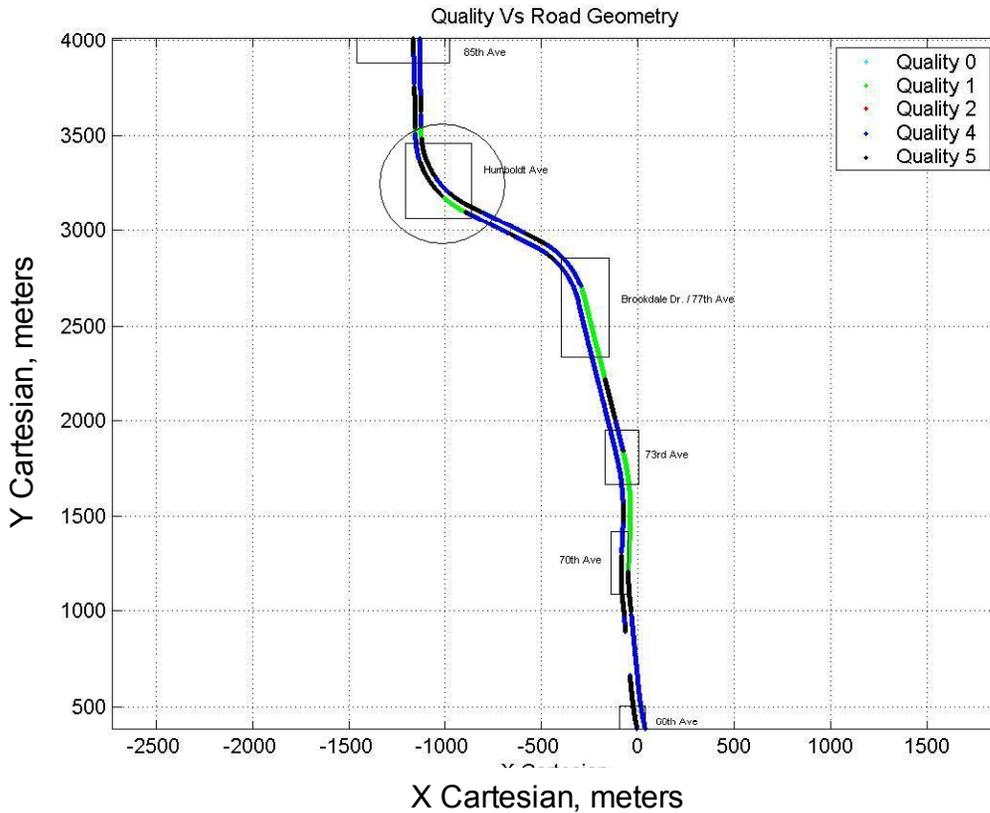


Figure 8. CDPD coverage on the Minnesota Trunk Highway 252 corridor. Green and black lines indicate areas where CDPD coverage is unavailable on the corridor. Coverage can only be considered poor here.

Clearly, CDPD coverage is inadequate to provide corrections on a wide scale basis. AT&T, the provider of our CDPD coverage, has no plans to widen their network. Instead, their business plan has changed to GPRS services as a replacement for CDPD.

This situation leaves one choice for GPS correction broadcast: digital cell phones capable of wireless modem operation. The IV Lab uses Verizon as a cellular phone provider. Initial experiments indicated that Verizon provided excellent coverage of both the 252 corridor and the University Transitway. (These initial experiments were to make cell phone voice connection and chat the length of the corridor. No dropouts were located during multiple trips up and down the 252 corridor, indicating this approach would work.)

The IV Lab cell phone was upgraded to a Tri-Mode phone, and a data kit procured. During this time, the IV Lab designed and implemented a scheme to provide GPS corrections with a cellular phone. The IV Lab VRS Server was used to provide corrections to the roving GPS receiver in the system described below. (In June of 2002, Trimble provided to the IV Lab a mirror site to the Mn/DOT VRS system to provide system redundancy and provide a test bed for testing new ideas and approaches to VRS applications. The IV Lab was the first group to implement a cell phone based communication link with the VRS.)

The process is initiated at the bus side. After the control computer boots, the bus coarse position as measured by the GPS receiver is sent to the vehicle control computer. The vehicle control computer instructs the cell phone to connect to the Verizon IP server. After that connection is made, the vehicle control computer connects to the IV Lab VRS Server through the Verizon IP server. After the connection is made, the coarse position is passed to the VRS Server. In turn, the VRS system passes the CMR correction back through the Verizon IP server at a rate of 1 Hz to the vehicle control computer, which in turn passes the correction to the GPS receiver. The dataflow diagram is shown in Figure 9 below.

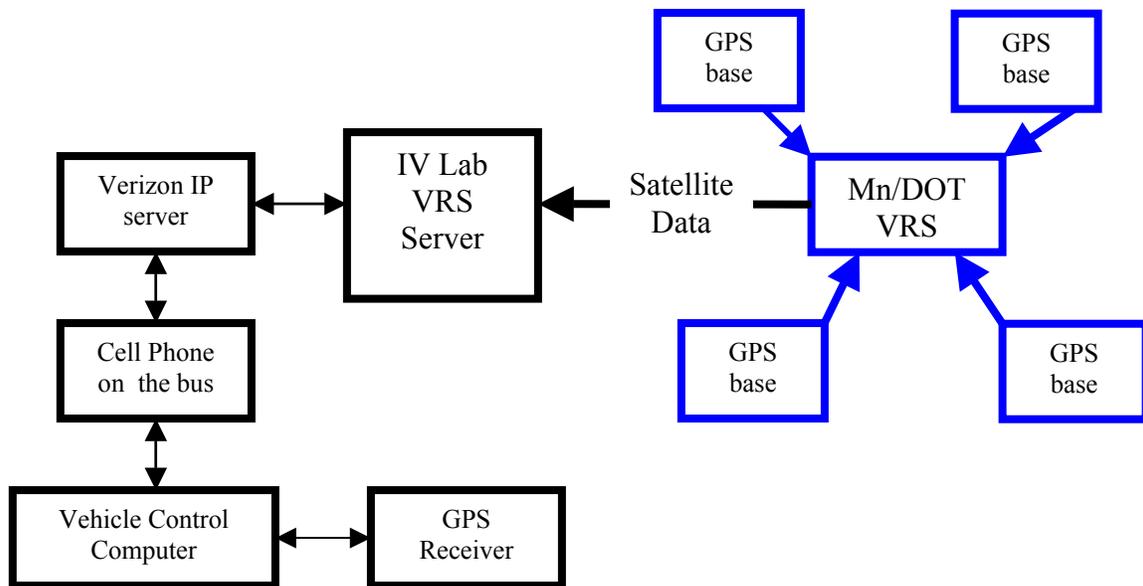


Figure 9. Data Flow Diagram for VRS based corrections using a cell phone as a wireless modem. Blue boxes and arrows represent components on the Mn/DOT side; black boxes and arrows represent IV Lab / Technobus components.

In the event that the cell phone connection to the Verizon IP Server is lost, the vehicle control computer no longer receives GPS corrections. Should the corrections not arrive for a period of one minute (this period can be adjusted by the system developer), the control computer initiates a new connection, and the connection process is repeated.

This cellular phone method was used to provide DGPS corrections for the Pilot Human Factors study associated with the FTA Lane Assist Project. During the approximately 80 hours subjects were trained and tested, the cell phone connection provided reliable, robust connections to the VRS server. Dropped lines were not an issue, and only on occasion were data transmissions temporarily unavailable. Unfortunately, as part of this study, data regarding connectivity and data throughput was not recorded during these tests. However, should further driver testing be carried out, data related to correction reliability will be collected.

However, for analysis purposes, the cell phone coverage for GPS corrections was measured in a set of experiments. During this experiment, a connection was made to the Mn/DOT VRS server, and route 252 was driven repeatedly both north and southbound. The results of the test are shown in below Figure 10.

Clearly, using a cell phone as a wireless modem and using Verizon as a provider of cellular coverage is a technically feasible means with which to take advantage of the Mn/DOT VRS system. As it turns out, based on our results, Mn/DOT is in the process of converting their survey operations from CDPD to cell phone based wireless modems. For their application, CDPD coverage was excessively spotty.

The main concession associated with using cell phones for DGPS corrections is the cost of airtime. For surveyors, this cost can be justified quite easily as the length of time at a particular site is relatively short. For transit use, however, costs can become relatively expensive. However, it is likely that for a wide scale deployment, Metro Transit can negotiate with a cellular provider to determine a reasonable pricing structure. For the human factors testing undertaken with this system, 2000 minutes of connection time per month cost \$150.

Finally, a demonstration of the system using VRS and cell phone based corrections is provided on the CD included as an appendix to this report.

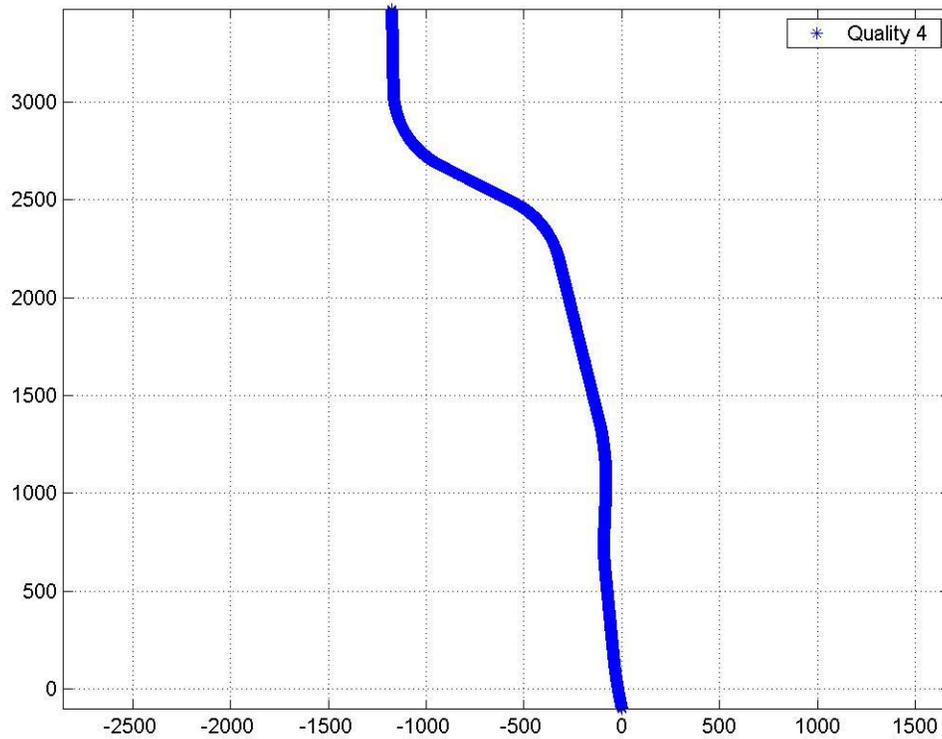


Figure 10. DGPS performance on Minnesota Trunk Highway 252 north of I-94 and south of East River Road. Using VRS, at least one of the two GPS receivers on the Technobus was able to consistently “fix” the length of the corridor, providing reliable centimeter level positioning.

Chapter 4. Infrastructure Build.

The infrastructure needed to support the bus driver assistive system includes the real-time provision of the corrections for the DGPS system and the creation of the geo-spatial database needed for lane keeping and forward collision avoidance.

Selection of a “base station” was described in Chapter 2 above. To summarize, the IV Lab leveraged the capability of Mn/DOT’s VRS system to support bus-only shoulder operation. A digital cell phone was used to broadcast correction data from the VRS server to the Technobus.

The remaining infrastructure element is the geospatial database. A description of the IV Lab database, including database elements, database accuracy, and database query performance and query times are described in [4] and [5].

The geospatial database used for a driver assistive system contains a description of the local landscape in terms of elements important for vehicle navigation. Elements included in the database include lane boundaries, lane centers, turn lanes, guard rails, drivable surfaces, etc. As a vehicle proceeds along a corridor described by the database, the on-board computer system queries the database based upon present GPS location measurements. Information returned from the database is then used by the computer process which executed the query. Subsystems which use the information contained within the database include the lane assist system, the forward collision avoidance system, and the side collision avoidance system.

Two specific databases were created to support these bus operations. One was created for the University Transitway, and the other was created for Minnesota Trunk Highway 252 between I-94 and East River Road in Brooklyn Center, Minnesota (a first tier suburb of Minneapolis). These were briefly discussed in Chapter 2.

The geometries of the roadways on which the Technobus operates are well structured and relatively simple. The databases which represent these roadways reflect this simplicity, and facilitate relatively quick map development. This bodes well for BRT applications where route and road construction may motivate frequent changes to the database. A simple map structure accommodates database updates.

Typically, elements in the geospatial database are located to an accuracy of approximately 20 cm or better. This 20 cm error includes vehicle position and orientation inaccuracies, paint stripe width errors, errors in lane stripe marking, and deviations from design to “as built.” For a driver assistive system used for low visibility conditions, 8 in (20.3 cm) accuracy is sufficient to keep a vehicle properly placed in a twelve-foot wide lane. However, when dealing with narrow lane assistance systems, 8 in (20.3 cm) accuracy becomes insufficient to provide guidance accuracy and ride quality needed in a transit system.

Transit buses used by Twin Cities Metro Transit measure 9.5 feet (2.9 m) wide across the rear view mirrors, and approximately 8.5 feet (2.6m) across the dual rear wheels. Typical shoulders are 10 feet (3.1 m) wide. This leaves a driver 3 in (7.62 cm) on either side of the mirrors in which to maintain lane position at the mirrors, or 8 in (20.3 cm) on either side of the bus to maintain lane position at the rear wheels. Clearly, a map accurate to 8 in (20.3 cm) is inadequate to reliably keep a bus in its proper place in the lane while maintaining the ride quality passengers require.

To accommodate this accuracy requirement, new data collection and reduction techniques were developed. Typically with maps created for low visibility conditions, a single pass over the lane is sufficient to collect data of sufficient accuracy and density to meet the 8 in (20.3 cm) accuracy specification. Multiple passes are required to collect enough data to enable *spatial* averaging of noisy road data. The difficulty then becomes the tradeoff between the accuracy gains made from averaging and the data density lost due to that spatial averaging process.

The geospatial database used for Trunk Highway 252 was arrived at through an *ad-hoc* optimization procedure whereby an initial database was created from a small number of runs. After the data were processed, the database was evaluated through in-vehicle testing where the database was compared with the actual roadway. Problem areas were identified, and additional data were collected and processed. This procedure was repeated at problem areas until the required accuracy and spatial density of the database was sufficient to provide accurate guidance and ride quality.

The problem of optimal database generation is an ongoing research project at the University of Minnesota IV Lab. Key parameters affecting the generation of the geospatial database include the accuracy of the data collected, the amount of data collected, spatial averaging to complete, and the validation of the completed database. It is important to note that the structure of the database as well as methods used to construct these databases are presently pending US patents ([6], [7]).

Clearly, presentation of the entire database representing either the University Transitway or Trunk Highway 252 is difficult in this context. Therefore, graphical representations of the data contained within the databases are presented in Figure 11- Figure 13.

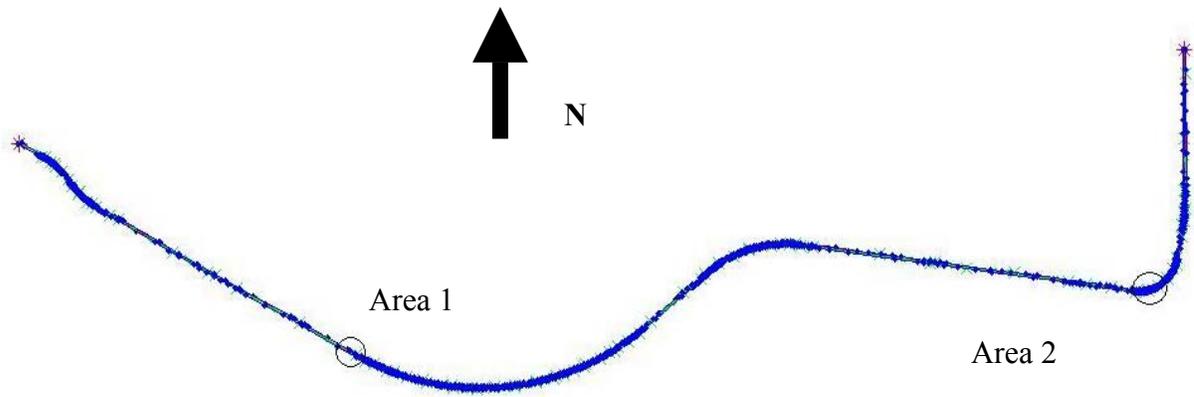


Figure 11. Graphical representation of the geospatial database for the University Transitway. To show map details, the circled areas are “zoomed in” and illustrated below. “Area 1” is the circle to the left; “Area 2” is the circle on the right.

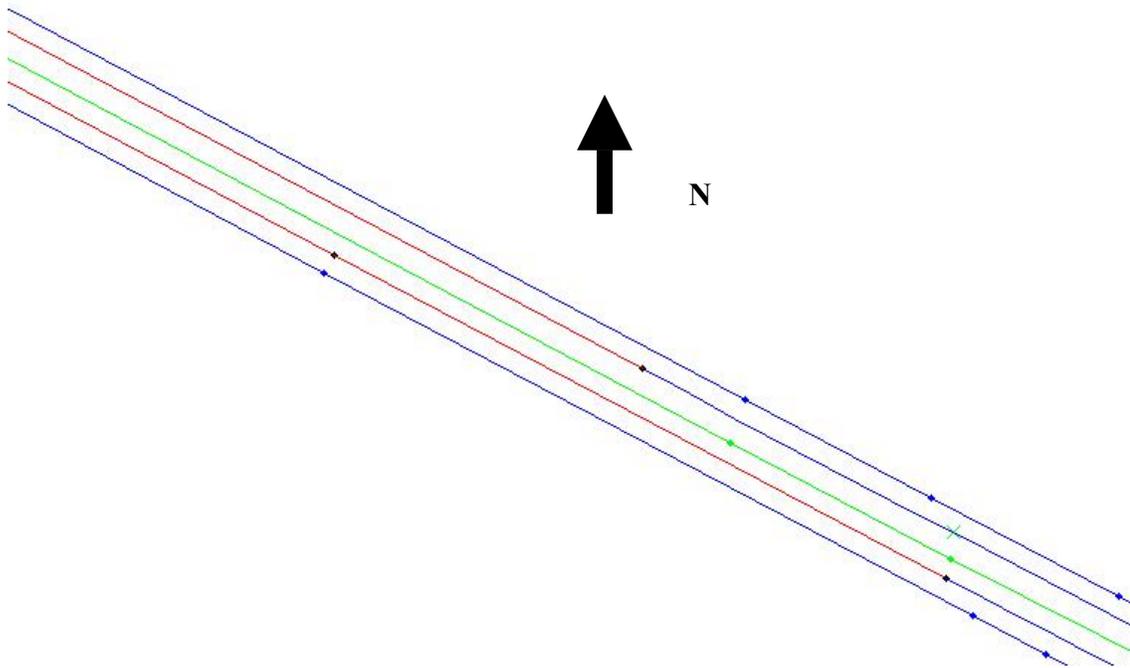


Figure 12. “Area 1” zoomed in. “Dots” represent geo-located elements found within the database. The “outside” lines (blue) represent the outer boundary of the transitway drivable surface (the curbs, where present), the green line separates the two lanes, and the red/blue lines between the green and outside blue lines represent the lane centers.

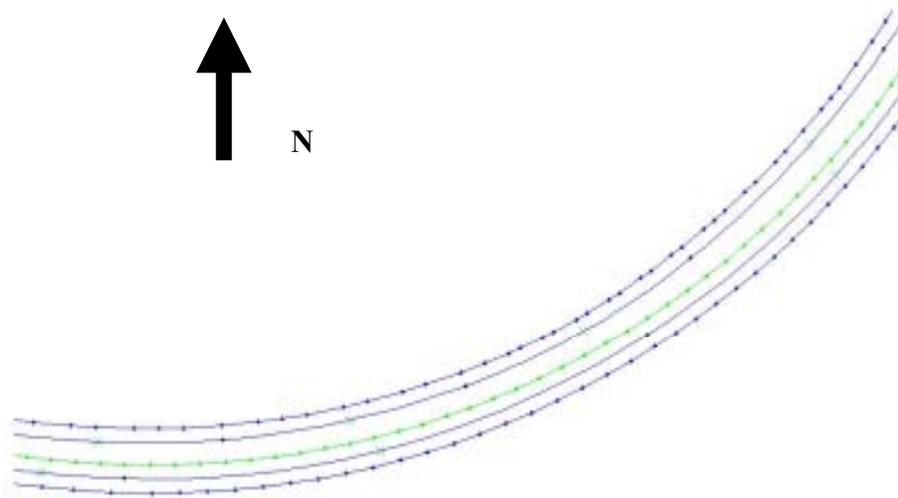


Figure 13. “Area 2” zoomed in. “Dots” represent geo-located elements found within the database. Note that the density of points for the curved portion of the database is much higher than that for the straight sections (see Figure 12). The “outside” lines (blue) represent the outer boundary of the transitway drivable surface (the curbs, where present), the green line separates the two lanes, and the blue lines between the outside blue lines and the green line represent the lane centers.

The transitway geospatial database is simple with respect to the fact that few intersections cross the transitway, traffic volumes carried by these intersections are low, and very few features other than the traffic lanes are located near the transitway. Picture 5 below shows the benign environment adjacent to the University Transitway.



Picture 5. Photo of Transitway looking west at the Westgate intersection.

Trunk Highway 252 represents a more complex environment. On Trunk Highway 252, drivers face 2 or 3 lanes of traffic, turn lanes, intersections with traffic islands, etc. To support bus-only shoulder operation in this environment, a database with greater complexity than that used for the University transitway is needed.

A graphical representation of the database which represents Trunk Highway 252 is shown in Figure 14 below. For the work described herein, the database covered Highway 252 northbound from 69th Ave N to 85th Ave N; southbound, the database covered from 85th Ave N to 73rd Ave N. North of 85th Ave N, Trunk Highway 252 was not certified for bus-only shoulder use, so the database was not extended north of 85th Ave N.

Trunk Highway 252 south of 73rd Ave N was also not covered by the geospatial database. Adjacent to the southbound lane are a stand of trees extending from 73rd Ave N to 69th Ave N. These trees block the GPS constellation, thereby rendering GPS accuracies too poor for lane assistance. Should such a system be deployed, it is likely that the trees would be trimmed to allow GPS satellite signals to pass.

It is important to note that the geospatial database constructed for Trunk Highway 252 only covers the right shoulder and the lane adjacent to the right shoulder. This was done primarily because the tests performed by the IV Lab only involve the shoulder and the adjacent lane. Additional lanes could be added to the database, but were not because they were not needed.

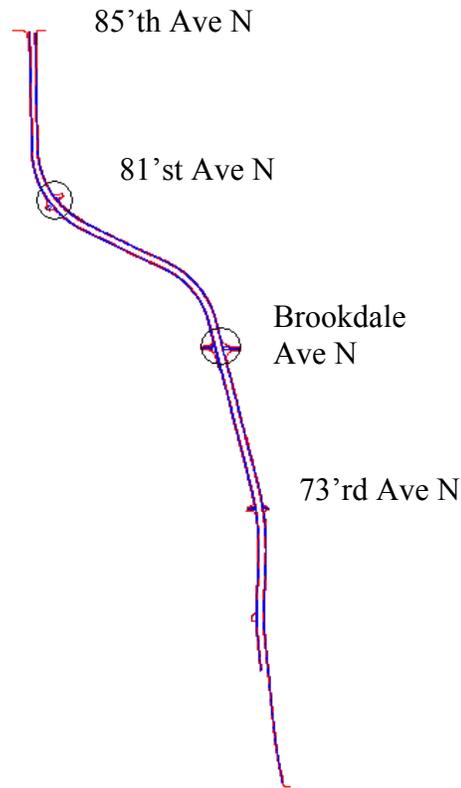


Figure 14. Plan view of graphical representation of geospatial database for Minnesota Trunk Highway 252 north of I-94; the area covered by the geospatial database is bounded by 73'rd Ave. North at the south end and 85'th Ave N. on the North end. Only the northbound lane south of 73'rd Ave. North is included because of the tree canopy blocking GPS signals southbound south of 73'rd Ave. N.

The intersection at 81'st Ave N is shown in Figure 15, and the intersection at Brookdale Ave N is shown in Figure 16.

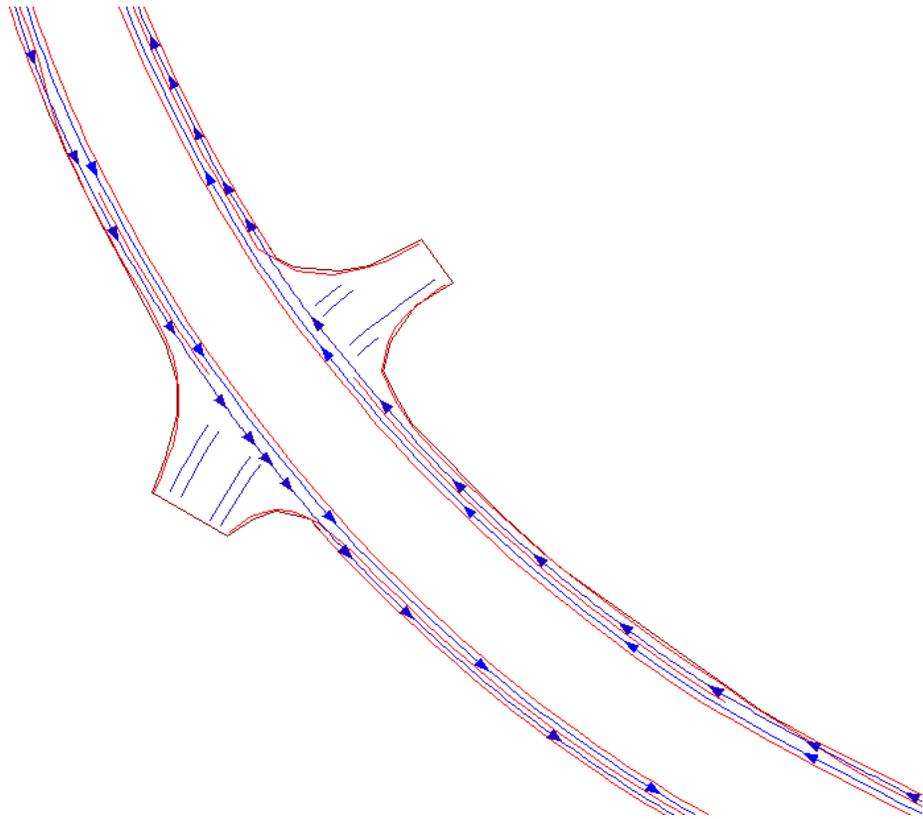


Figure 15. Intersection of Highway 252 and 81'st Ave N. Intersecting road is also incorporated into the geospatial database. Note that only right shoulder and adjacent lane are included in the database. Arrows indicate direction of travel on that lane (one of the attributes associated with lane information).

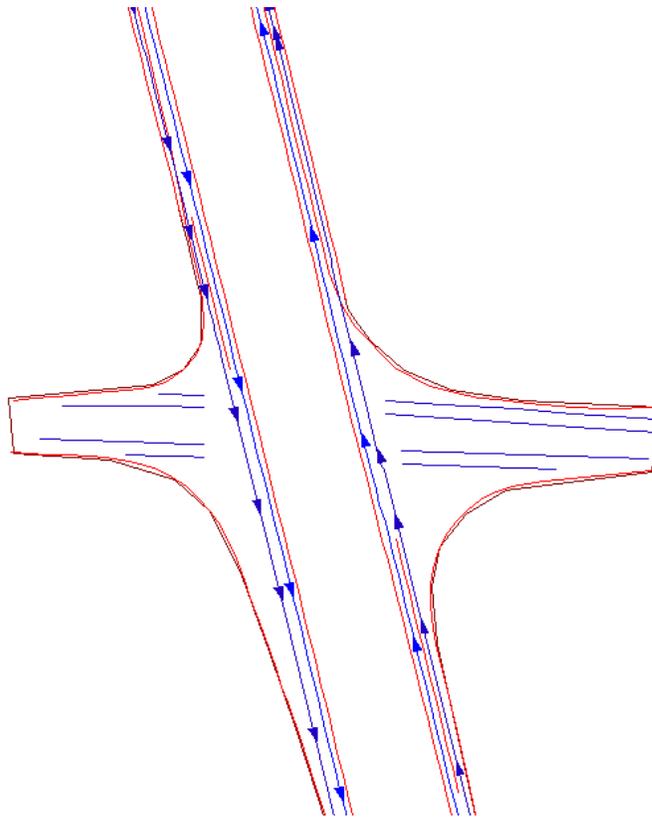


Figure 16. Intersection of Highway 252 and Brookdale Ave N. Intersecting road is also incorporated into the geospatial database. Note that only right shoulder and adjacent lane are included in the database. Arrows indicate direction of travel on that lane (one of the attributes associated with lane information).

On Trunk Highway 252, a bus operating on the shoulder must pass through the intersections indicated in Figure 14. At these intersections, the ten foot (3.05m) wide road shoulder widens into a twelve foot (3.7m) turn lane, and after the intersection is passed, back to a ten foot wide shoulder. Each driver has a preferred trajectory through these intersections; one of the issues facing the creator of the geospatial database is the choice of trajectory through the intersection and the transitions from ten to twelve foot wide lanes.

Included as an appendix to this report is a CD-ROM which includes video files of the Technobus operating on Trunk Highway 252 in a lane-assistance mode. The videos contained on that CD best illustrate some of the choices made to help a driver guide the Technobus through the intersection. What is shown is that through the intersections where the bus travels through a twelve foot wide lane, the preferred trajectory is that which keeps the bus close to the left shoulder boundary. This minimizes the likelihood that the bus will hit the traffic islands at the intersection and maintains ride quality as deviations in the lateral position of the bus are minimized.

Chapter 5. Bus Mechanics and Dynamics.

The two subtasks associated with Task 4 of the project involve actuation of the steering gear, and the use of the steering gear to control the lateral position of the bus in the narrow lane. In this chapter, the steering gear design is described first, and the lateral control algorithm is discussed second.

Steering Mechanism.

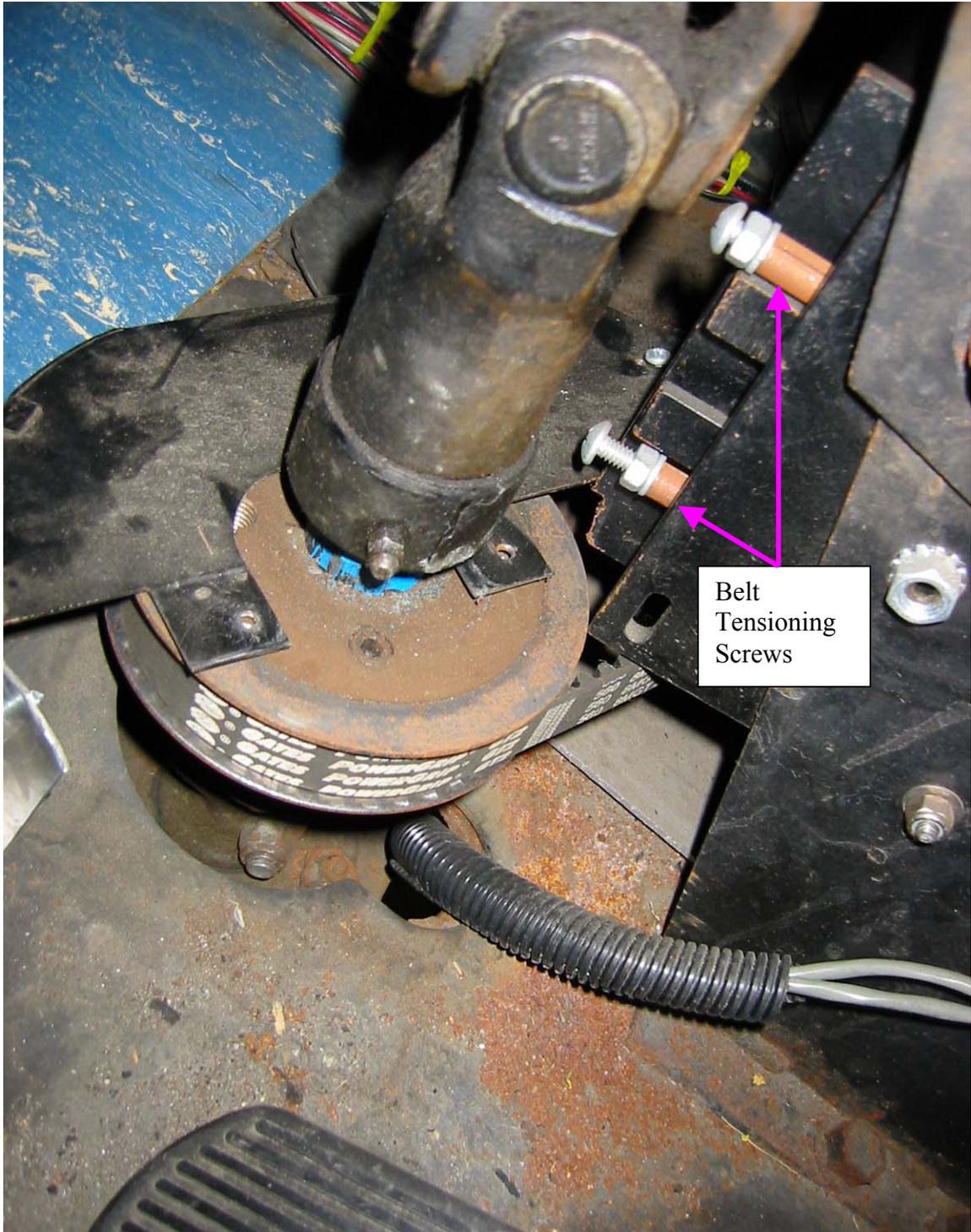
The steering actuator design is based around a Kollmorgen servo motor. The steering actuation system consists of a Kollmorgen servomotor (model MT-308A1-R1C1), a Kollmorgen servo amplifier (model number CR-03250-0000) and cable assembly (model number CS-SS-RHAIHE-06). Power transmission from the servomotor to the steering mechanism is via a toothed belt / pulley mechanism, with a 3:1 speed reduction from the motor to the steering shaft. Power transmission parts were sourced from Gates using Polychain components. System feedback is provided by a “semi-absolute” encoder mounted in the end of the servomotor. Semi-absolute in this situation means that the encoder is absolute upon power up, using its power-up position as “zero.” On power down, that “zero” is “forgotten”, and a new “zero” is designated the next time the system is powered.

Lack of room under the bus combined with the corrosive environment in which a Metro Transit bus must operate motivated the decision to locate the steering actuation system inside the bus. Compact motor design facilitates this decision by preventing interference between the servomotor and the drivers’ left foot. Picture 6 illustrates the mounting of the steering actuator in the bus, and that the system is designed so no interference exists between the drivers’ left foot and the turn signal control panel. (Design drawings are provided in Appendix A).



Picture 6. Technobus steering actuator. The steering servomotor is mounted to the rigid support which keeps the steering shaft in place. The steering motor is sized so as to not interfere with the drivers left foot, which is normally kept on the turn signal control panel. The steering shaft is driven by the servomotor via 3:1 Gates Polychain belt/pulley system.

Because steering gear is safety critical for any highway vehicle, Metro Transit required the IV Lab to perform a Failure Modes and Effects Analysis of the steering actuation system. The result of the FMEA effort is provided in Appendix B of this report. This FMEA is based on a standard used by the FTA for all emerging technology applied to FTA buses. The results of this analysis were submitted to Metro Transit; no feedback was provided, so the standing assumption is that the analysis was sufficient for their application.



Picture 7. Right side view of steering actuation system. Safety guard is removed to show drive pulley and Gates polychain belt drive. Belt tensioning screws are visible in upper right. Sheathed cables are power/signal cables from forward looking Eaton Vorad Radar.

Lateral Control Algorithm.

The lateral controller used on the bus is based on the lateral controller used for the SAFELOW research vehicle. The SAFELOW lateral controller is described in [1], and the lateral controller used on the Technobus is based on the work described therein.

Lateral error is defined as the distance from the vehicle center to the lane center, and the function of the lateral control system is to maintain a desired lateral position within the desired lane of travel. Lateral error is computed by comparing the global position of the bus as provided by the on-board DGPS system to the location of the lane center as provided by the on-board geospatial database. Lane information is provided to the lateral controller via position referenced queries to the geospatial database.

The lateral controller is a PD controller with a feed forward term. The output of the lateral controller, δ , is a steering command to the servo motor which drives the steering system. Mathematically,

$$\delta \equiv \delta_P + \delta_D + \delta_{FF} \quad (1)$$

where δ_P is the proportional term, δ_D is the derivative term, and δ_{FF} is the feed forward term.

The proportional term reduces the lateral error. The derivative term adds damping compensation to reduce lateral oscillations. The feedforward term uses the lane information provided by the geospatial database to anticipate changes in the bearing of the road and position the steering wheel in the proper direction.

Figure 17 illustrates a vehicle traversing a curve on a road; Wb represents the vehicle wheelbase, y represents the lateral error, and r represents the radius of the curve traversed by the vehicle as provided by the geospatial database. With these parameters, it follows that

$$\delta_P = k_p y,$$

$$\delta_D = k_d \dot{y}, \text{ and}$$

$$\delta = k_{ff} \frac{Wb}{r},$$

where y is the lateral error, \dot{y} is the lateral error rate, Wb is the vehicle wheelbase, r is the corner radius, k_p is the proportional gain, k_d is the derivative gain, and k_{FF} is the feedforward gain.

The proportional, derivative, and feedforward gains are not constant, but vary based vehicle speed and curve geometry. The lateral gain controller structure, complete with gain scheduling rules, is shown in Figure 18.

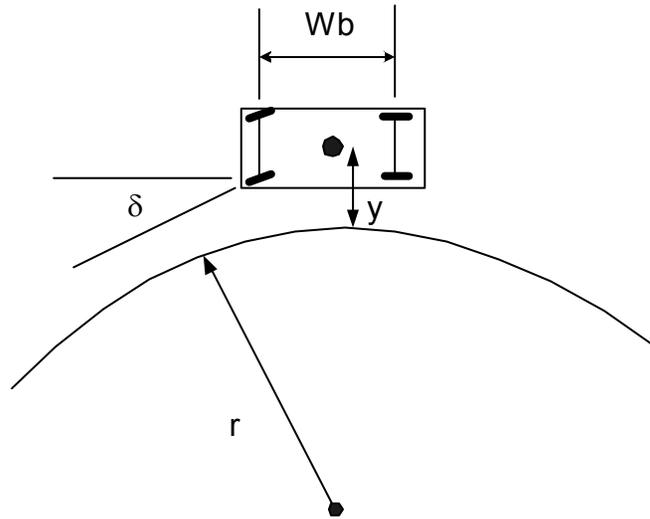


Figure 17. The correction term (δ) is obtained from the lateral error (y), the radius of curvature of the road (r), and the wheel base (Wb).

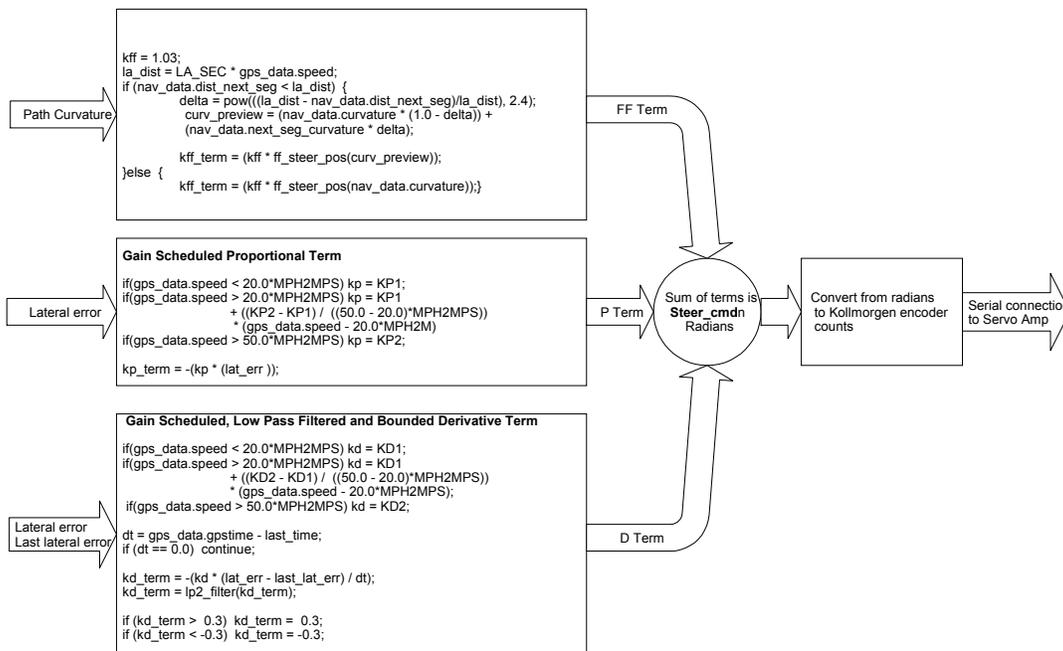


Figure 18. Lateral controller block diagram. The upper block defines the feed forward gain schedule, the middle block defines the proportional gain schedule, and the lower block defines the derivative gain schedule.

This system is designed to provide torque feedback to a driver operating a bus in a narrow lane. Bus drivers want (and should be given) the ability to override the assistive system should he/she see fit. To enable a driver to override the system when necessary, the maximum torque which can be applied by the servomotor is software limited. The limit is set to a point where sufficient torque is applied so that the steering wheel can turn at low vehicle speeds (where steering effort is highest). All drivers who have used the bus have been able to override the system during tests.

In the following chapter, the operation and performance of the driver assistive system is documented.

Chapter 6. Driver Assistive System for Vehicle Guidance

In the previous chapter, the design of the lateral control system was discussed. In this chapter, the remaining mechanical, electrical, and computational systems are discussed and documented. After the design work has been documented, performance of the system is described both subjectively and objectively. Subjective measures are provided by a bumper mounted, downward facing camera aimed at the curb and gutter. As the Technobus is guided along the Trunk Highway 252 shoulder, the lateral deviation of the bus can be subjectively measured by observing the position of the curb and gutter relative to the camera. Objective performance measures are provided by measuring the lateral deviation of the bus from the center of the shoulder (where the center is defined by the geospatial database). The subjective measure of performance is available on the CD-ROM included with this report.

Design.

The Technobus driver assistive system can be divided into three fundamental subsystems; the positioning subsystem, the obstacle detection subsystem, and the driver interface subsystem. Implicit to this separation of subsystems are the computational systems on which all the subsystems operate. A data flow diagram representing the Technobus driver assistive system is provide in Figure 19 below.

Each of the subsystems is described briefly below.

Positioning Subsystem.

The primary vehicle positioning technology is dual frequency, carrier phase, RTK differential GPS. Two Trimble 13" Machine antennae are mounted near the front of the Technobus, and are connected to two Trimble MS750 GPS receivers. The installation of the GPS antenna on the Technobus is shown in Picture 8.

Dual antenna/receivers are used for three reasons. First, dual receivers are able to provide estimates of vehicle position, as well as heading and roll angles. A single GPS receiver can only directly provide position estimates; heading must be computed from sequential position estimates, and roll estimates are not available. Second, dual receivers offer a higher degree of robustness than does a single receiver; it is not uncommon that one of the two GPS receivers will achieve a "fix" solution while the adjacent receiver is unable to "fix." Multiple receivers increase the likelihood that a GPS solution sufficient for the lane assist system will be available.

The secondary positioning technology used on the Technobus is a Crossbow HDX six-axis IMU. The IMU provides three axes (x, y, and z) of acceleration estimates in the vehicle coordinate frame, and three axes (yaw, pitch, and roll) of vehicle rotation rates.

The IMU on the Technobus is mounted at the center of the front windshield; its mounting location is shown in Picture 9.

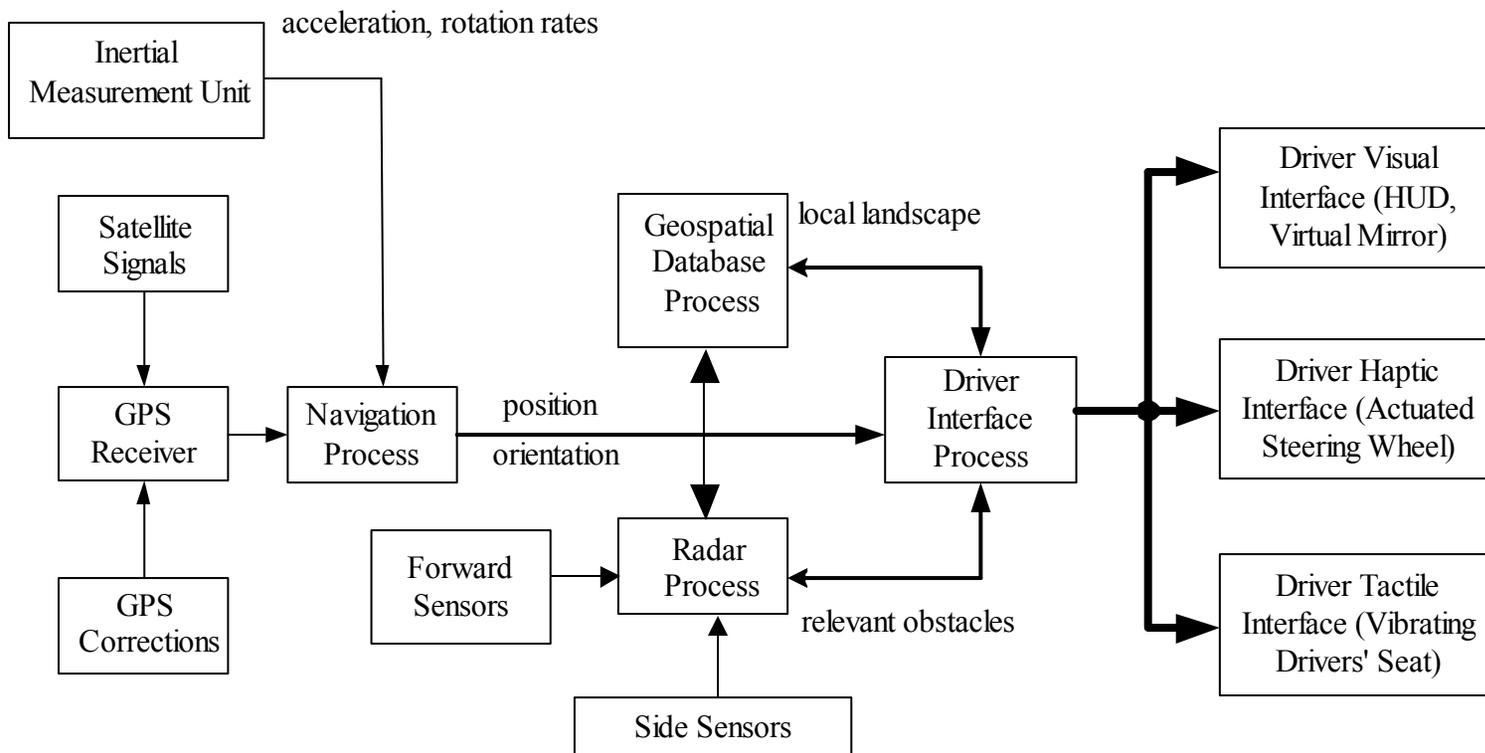
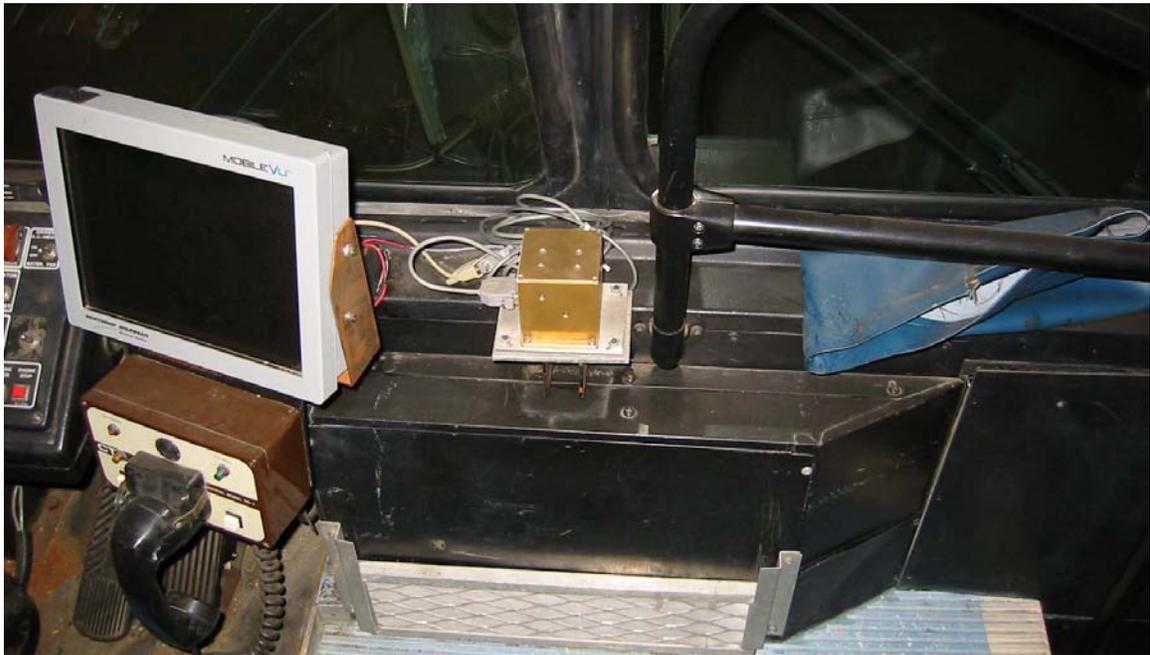


Figure 19. Technobus Driver Assistive System block diagram.



Picture 8. Front of Technobus showing GPS Antenna. Use of dual GPS receivers improves system robustness and provides vehicle position, heading, and roll measurements.



Picture 9. Photo showing the mounting of the Crossbow HDX IMU (gold colored cube) in the Technobus. IMU is mounted as far forward as possible to extract the highest sensitivity to bus lateral motion.

Both the GPS antennae and the IMU are mounted on the front of the Technobus to gain the highest possible measurement sensitivity to bus motion.

The primary purpose of the IMU is to augment the DGPS-based positioning system. In the event that the GPS is lost, the accelerations and rotation rates estimated by the IMU can be used to integrate the Euler equations of motion, thereby providing an inertially estimated global position of the bus.

The integration of DGPS and an IMU to achieve seamless positioning of a bus during the time DGPS is unavailable is an ongoing effort. With the latest version of the Trimble MS750 firmware (version 1.45), loss of satellite view results in an outage of precise (“fixed”) position estimates for a period of 5 to 10 seconds after the antenna is re-exposed to the satellite constellation. At the present time, IMU/DGPS integration is still relatively immature; the lane assist system is operational only when sufficiently accurate DGPS solutions are available.

DGPS solution accuracy can be divided into four categories: Autonomous, DGPS, “Float,” and “Fix.” Autonomous operation occurs when the GSP receiver either receives no DGPS correction or is not able to use what is provided. DGPS represents Code Differential positioning, with accuracies on the order of 1 meter. “Float” represents a DGPS solution where phase ambiguities are allowed to remain at non-integer values, resulting in position solutions with errors on the order of decimeters. A “fix” solution represents a DGPS solution where phase ambiguities are set to integer numbers for the final position computation, resulting in position solutions with errors on the order of centimeters.

To maintain ride quality for a lane assist system, torque feedback to the driver through the steering wheel is applied only when a “fix” solution is available. With position measurement qualities less than a “fix,” the steering system attempts to correct for relatively large swings in measured lateral error. Given the random nature of the float errors, these corrections are manifest in small, but annoying, lateral oscillations of the bus. Float solutions are of sufficient accuracy for feedback through the HUD and seat; ride quality does not suffer because a human driver cannot respond quickly enough to these random lateral errors. The errors associated with a “float” solution typically have relatively small bias, so a driver is able to maintain proper lane position.

Obstacle Detection Subsystem.

The obstacle detection subsystem is comprised of both a side and forward looking system. The left side obstacle detection system is different than the right side system; on the left side of the bus, the primary obstacles to be avoided are vehicles in the adjacent lane of traffic. Because the doors on the bus are on the right side, the primary object to be detected with the right-side system are passengers both leaving and entering the bus. Highway vehicles represent the focus of the forward obstacle detection system.

The side looking sensors used on the Technobus are Sick Scanning LIDAR units, model 221 equipped with internal heaters. These scanners provide 180 degrees of coverage, scan

at 10 Hz, have an effective range of 0.6 to 98.5 ft (0.2 to 30 m), and provide a resolution of 0.25 degrees. This Sick sensor as mounted in the Technobus is shown in Picture 10.

The output of the side obstacle detection system is provided in the following section of this chapter. A detailed development of the Virtual Mirror is provided in Volume II of this report.

Forward obstacle detection is provided by a pair of Eaton-Vorad T-300 automotive radar mounted on the front bumper of the Technobus. The performance of the T-300 radar has been fully documented in [8]. Specifications for the T-300 include sensitivity to closing rates of 0.25 to 100 mph (0.4 to 160 kph), an operating range of 3 to 350 ft. (0.9 to 106.7 m), and a host vehicle speed of 0.5 to 120 mph (.8 to 193 kph). The T-300 operates at a nominal frequency of 24.725 GHz over a temperature range of -40 to +185 F. The use of information provided by the T-300 radar will be illustrated in Chapter 7 of this report.

Table 3. Eaton Vorad T-300 Radar Specifications

| Description Value | Value |
|--------------------------|------------------------------|
| Operating Range | 3-350 ft (0.9 to 106.7 m) |
| Host Vehicle Speed | 0.5-120 mph (0.8 to 193 kph) |
| Frequency: | 24.725 GHz |
| Transmitted RF Power | 3.0 milliwatts (typical) |
| Temperature Range | -40 to +185 F |
| Vibration Range | 7G's, 10 to 2000 Hz |
| Field of View | +/- 0.1 degrees |
| Azimuth resolution | 0.2 degrees |

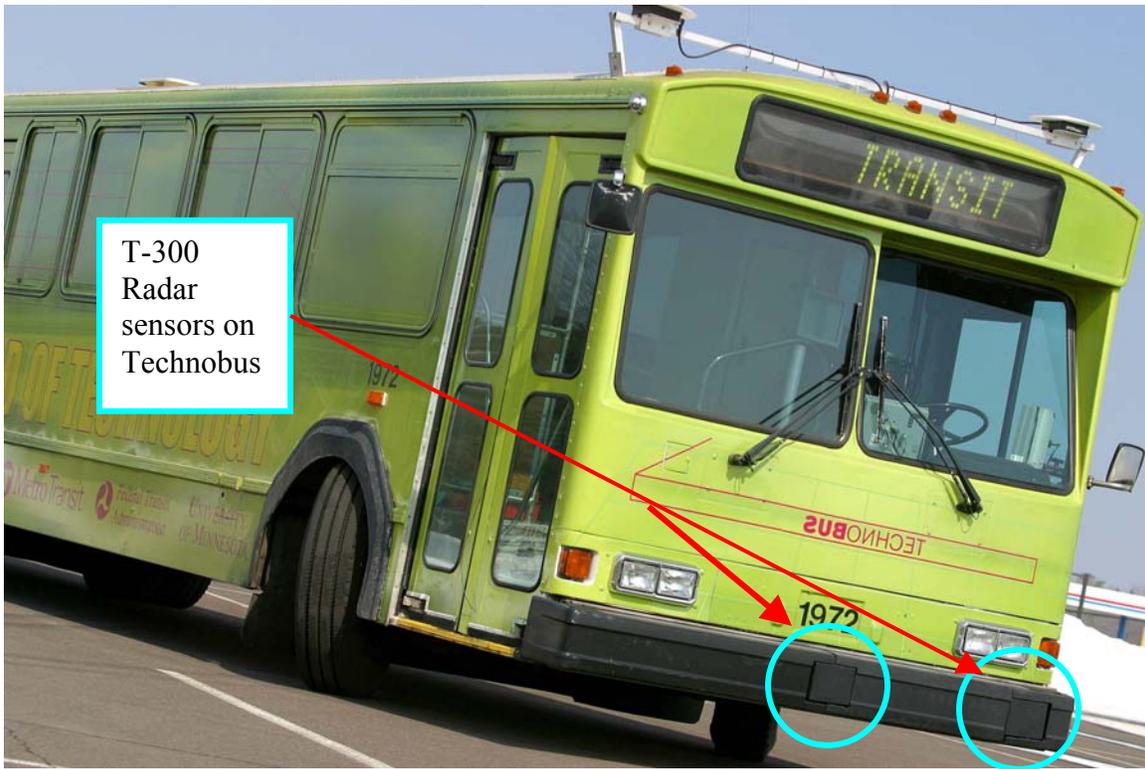


Picture 10. Scanning LIDAR sensor on left side of Technobus. Identical sensor is located on the right side of the bus. Image processing of left side sensor is optimized to detect vehicles adjacent to the bus; image processing of right side sensor is optimized to detect passengers entering and exiting the bus.

Driver Interface Subsystem.

The driver of the Technobus is provided feedback via three modalities: visual, haptic, and tactile. Auditory feedback was removed as a candidate early on in the design process because of the negative impact it was likely to have on the passengers in the bus.

Visual feedback is provided to the driver via the Head Up Display and the Virtual Mirror. The HUD is designed to provide the driver information regarding the position of the bus on the bus only shoulder as well as forward collision avoidance. Picture 3 presented the view a driver has through the HUD while the system is in operation. Picture 12 below illustrates how the system is installed in the driver's area within the bus "cab."



T-300
Radar
sensors on
Technobus

Picture 11. Front of Technobus showing location of two Eaton Vorad T-300 radar mounted on the front bumper. Use of dual radar provides fault detection capability, fault tolerance for forward obstacle detection, and a wider field of view compared to a single radar unit.

The driver is provided two Virtual Mirror displays; a display on the left side of the bus to provide obstacle information regarding the left side of the bus, and a display on the right side of the bus to provide information regarding passengers exiting and entering the bus.

The Sick sensor scans in just one horizontal plane; therefore, pattern recognition techniques are used to match output with obstacle characteristics to determine whether a target is present. For the left side system, vehicles are the primary target of concern. For the left side, the pattern recognition program is searching for lines and corners which represent the side and ends of adjacent vehicles, respectively. On the ride side, passengers are the target of primary concern. In this case, a pedestrian breaking a plane of light appears semi-circular, and is identified as a pedestrian.

The Virtual Mirror optimized for pedestrian tracking is shown in

Picture 13 and Picture 14 below.



Picture 12. HUD System as it is mounted in the Technobus. Combiner and projector are mounted to a research grade (i.e., highly configurable) mechanical mount.



Picture 13. View of the Virtual Mirror display for the right side of the Technobus. This configuration is optimized for pedestrian tracking. The location of the obstacles with respect to the bus are shown in Picture 14.



Picture 14. Objects and their position with respect to the Technobus corresponding to the view of the Virtual Mirror illustrated in

Picture 13.

System Hardware.

The final component needed to support a driver assistive system is the computer hardware on which system software runs. The Technobus uses three separate computers to run system software.

Three graphical displays provide information to the Technobus driver: the Head Up Display, the Left Virtual mirror, and the right Virtual Mirror/Driver Information Panel. Because PC based computers can only support a single video card, three computers are required.

Because of the research nature of the Technobus (it is not used for regular passenger operations), a significant amount of “real estate” inside the bus was dedicated for computational equipment. A steel cabinet with an integral 19 in (0.48 m) equipment rack was procured, and a steel frame was fabricated to support the cabinet on the bus. The passenger seats directly behind the driver’s seat were removed, and the equipment cabinet installed in that location as shown in Picture 15.



Picture 15. Equipment cabinet on Technobus research vehicle. Cabinet sits over left front wheel on a custom steel frame where the forward most center facing seats are typically mounted. Cabinet is approximately four feet (1.2 m) tall. Oak veneered box to cabinet left covers AC inverter, battery equalizer (splits 24 VDC to 12VDC), and amplifier for servo motor.

Mounted inside the cabinet are the Trimble MS750 GPS receivers, power supplies and communication interfaces for the Eaton Vorad forward looking radar, a power bus, Ethernet hubs, external serial port connectors, and the computers on which the system software runs. The equipment, as installed in the Technobus, is shown in Picture 16.

Power to this equipment is provided by the on-board vehicle 24 volt system. A battery equalizer is used to provide 12 volt power to those components which cannot use 24 volt power. AC power is also provided to the bus (primarily to power laptop computers) with a 1500 Watt inverter.

System performance: Lateral Guidance.

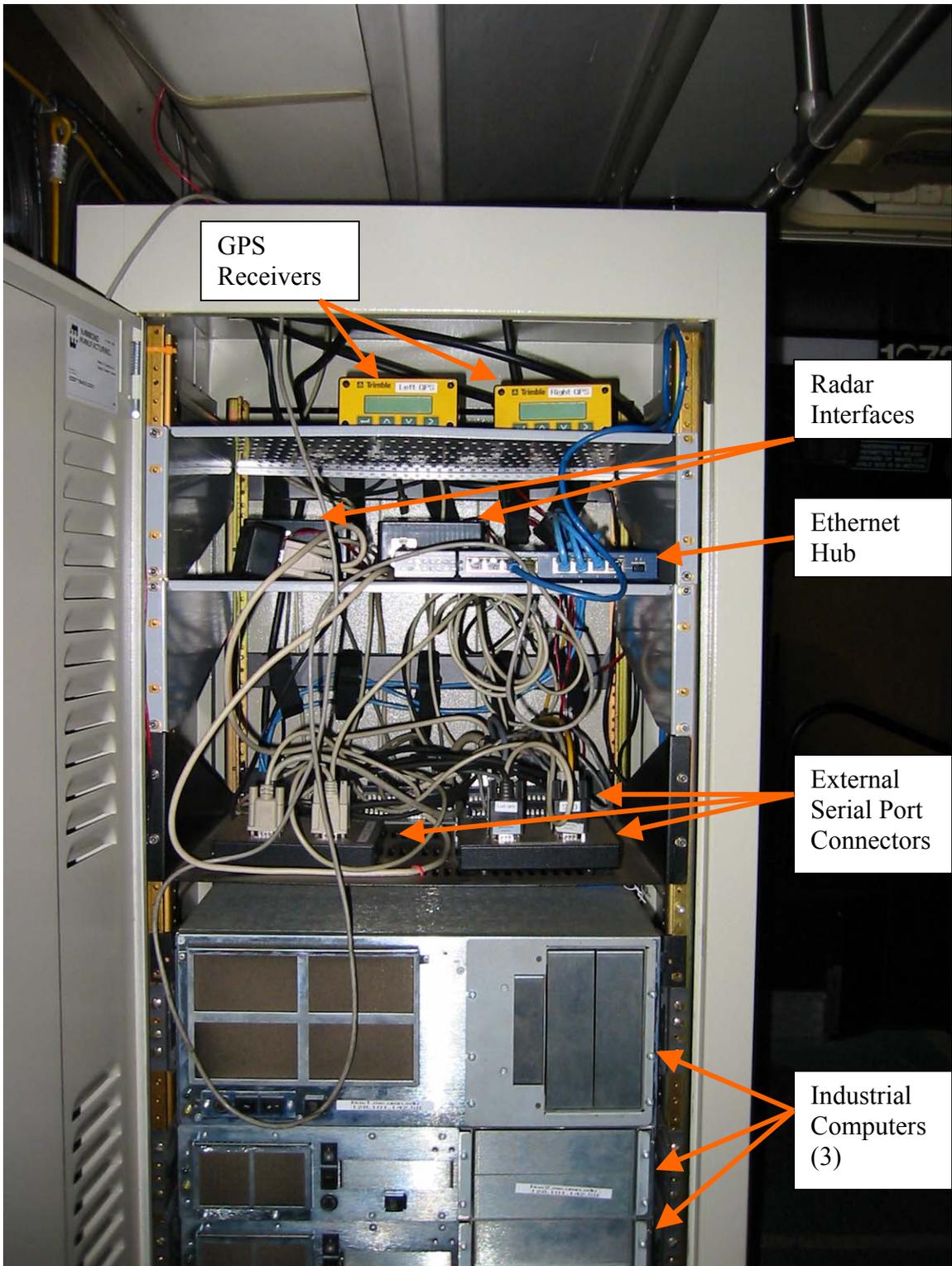
It is difficult to objectively quantify the performance of a driver assistive system; the distinction between driver and assist system should become “fuzzy” with a well integrated system.

As such, system performance will be quantified with *no* interaction between the driver and the driver assistive system. In this situation, the relative measure of performance of the system becomes the accuracy with which the system is able to maintain a desired lateral position in a desired lane.

The topology of Trunk Highway 252 is essentially flat. The bus-only shoulder pavement is in relatively good condition, but does suffer from the presence of drain grates, occasional broken pavement, some washboard conditions, slight crowns, and undulating sections. The guidance system is relatively robust to these road conditions. This robustness can be seen in the response of the system shown below in the following figures as well as in the video provided on the CD included with this report.

Test conditions were as follows. The Technobus was operated with IV Lab personnel in the driver’s seat. For the testing, the driver was to not operate the steering wheel unless intervention was needed to maintain safety. The driver was to maintain the speed of the bus at 35 mph (56.3 kph) whenever possible to illustrate the performance of the system at the maximum speed allowed by law in Minnesota.

Figure 20 and Figure 21 below provide an illustration of the system lateral errors as the system is “driven” on the Highway 252 shoulder at an average speed of 35 mph (56.3 kph). As is shown, performance is quite good. Figure 20 shows that speed was held at approximately 35 mph (56.3 kph), with a standard deviation of 2.8 mph (4.5 kph). Figure 21 shows that the mean lateral offset was 2.2 in (5.6 cm), with a standard deviation of 5.2 in (13.1 cm).



Picture 16. Interior of Technobus equipment cabinet. GPS, Network, Radar Interface, serial ports, and computers are indicated.

The steering actuation motor utilizes a +/- 2.0 lbf-ft (2.7N-m) torque limit. Limiting steering wheel actuation torque at this value ensures that a driver will be able to overcome the lane assist system should he or she feel it is necessary to do so. The 2.0 ft-lb (2.7N-m) limit represents a compromise between the performance of the lane assist system and a level of comfort experienced by the driver. Increasing the torque limit would increase the speed of response of the lane assist system, but would decrease the ability of the driver to respond to critical situations.

As previously mentioned, the approach taken by the IV Lab is to mount the DGPS antenna as far forward as possible on the bus. In terms of feedback control, forward mounting of the antennae array provides the greatest position measurement sensitivity to yawing motions of the bus (i.e., when the bus is steered from left to right, the front of the bus moves a greater lateral distance than the rear of the bus). This high measurement sensitivity facilitates robust performance in terms of disturbance rejection. However, using the GPS antennae mounted forward to quantify lane keeping performance also increases its measurement sensitivity to disturbances. Mounting of the performance measurement antenna on the rear of the bus would show markedly decreased lateral error variance. Transit agencies must be careful when evaluating vehicles and/or technologies to ensure that measurement practices are consistent between vendors, and are designed to show the worst-case behavior.

To provide a second measure of bus lateral performance, a camera mounted on the front bumper, pointed at the ground, is used. The video clips included in the CD accompanying this report show the lateral position performance of the bus. It is important to note that the camera is mounted on the *front* bumper of the bus. Just as mounting GPS antennae on the front of the bus provides the greatest sensitivity to errors and disturbances, so to does the mounting of the camera in the front of the bus. Had the camera been mounted on the rear of the bus, lane keeping performance would have appeared even better. (Even with a forward mounted camera, the down looking camera shows excellent lane keeping performance by the Technobus.) This reinforces the notion that transit agencies considering lane assist and precision docking station must be cognizant of the relationship between sensor location and system performance measurement, and that measurements done by prospective vendors must be done consistently.

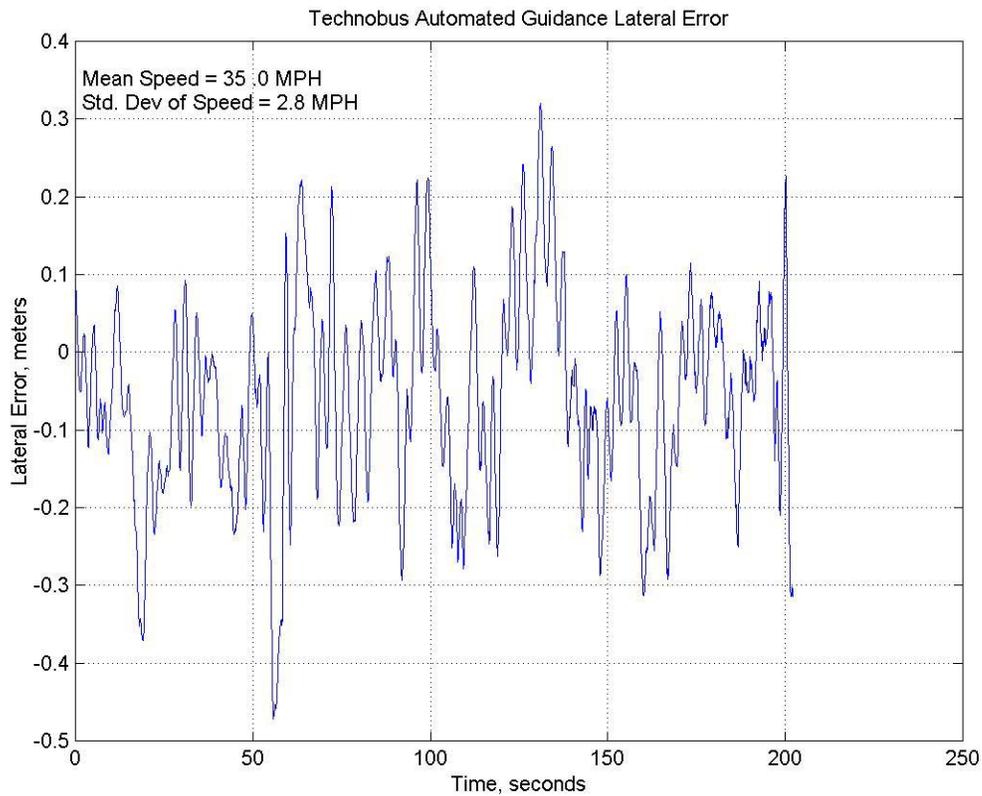


Figure 20. Technobus lateral error as a function of test time. Test speed was steady at 35 mph, with a small standard deviation of 2.8 mph (4.5 kph). This data is for one northbound trip up the test corridor. The trip duration was 202 seconds (about 3.5 minutes) at an average speed of 35 mph (56.3 kph) (the maximum allowable speed). This example was based on GPS alone with no inertial measurements used in the vehicle controller.

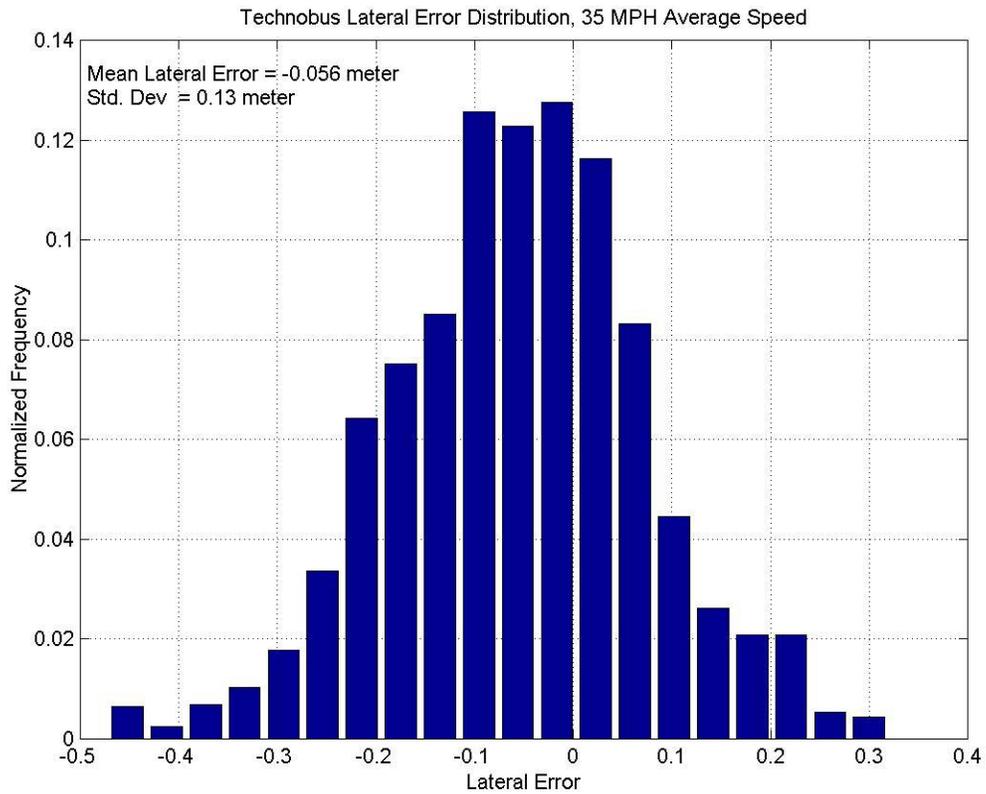


Figure 21. Distribution of lateral errors for the data of Figure 20 from Technobus testing. Mean error is -2.2 inches, (-5.6 cm), with a standard deviation of 5.1 in (13 cm). This data is for one northbound trip up the test corridor. The trip duration was 202 seconds (about 3.5 minutes) at an average speed of 35 mph (56.3 kph) (the maximum allowable speed). This performance would be difficult for a skilled human to replicate.

Chapter 7. Obstacle Detection

Both forward and side obstacle detection technologies were considered in this program. Forward obstacle detection was carried over from snowplow driver assistive systems; details including a description of that system and how it operates can be found in [1] and [8]. Implementation of the forward obstacle detection system on the Technobus will be discussed further in this chapter.

A substantial effort developing side obstacle detection and conveyance of side obstacle information was undertaken as part of this program. Volume II of this report deals with the development and execution of the virtual mirror side obstacle detection system. In this chapter, a brief overview of the virtual mirror is provided.

Forward obstacle detection.

The forward obstacle detection system is based on the Eaton Vorad T-300 radar sensor. Specifications for this radar system are found in Table 3. Two sensors are mounted on the front bumper of the Technobus as shown in Picture 11. Two sensors are used for two reasons: redundancy/fault detection and increased forward coverage.

Fault detection is achieved by comparing the returns from each radar; targets located in the overlap area should be identified by both radar as a valid target. If a discrepancy shows between the two radar, a fault exists. (It should be noted that in the four years the IV Lab has used EVT-300 radar, not a single unit has failed).

Considerable gains in the effective field of view of the obstacle detection system are achieved by placing a second T-300 on the left side of the Technobus. Given the relatively narrow field of view of a single sensor, using only one radar would leave a significant gap on the left side of the front of the Technobus. The gap, and the effect the additional sensor has on that gap is illustrated below in Figure 22.

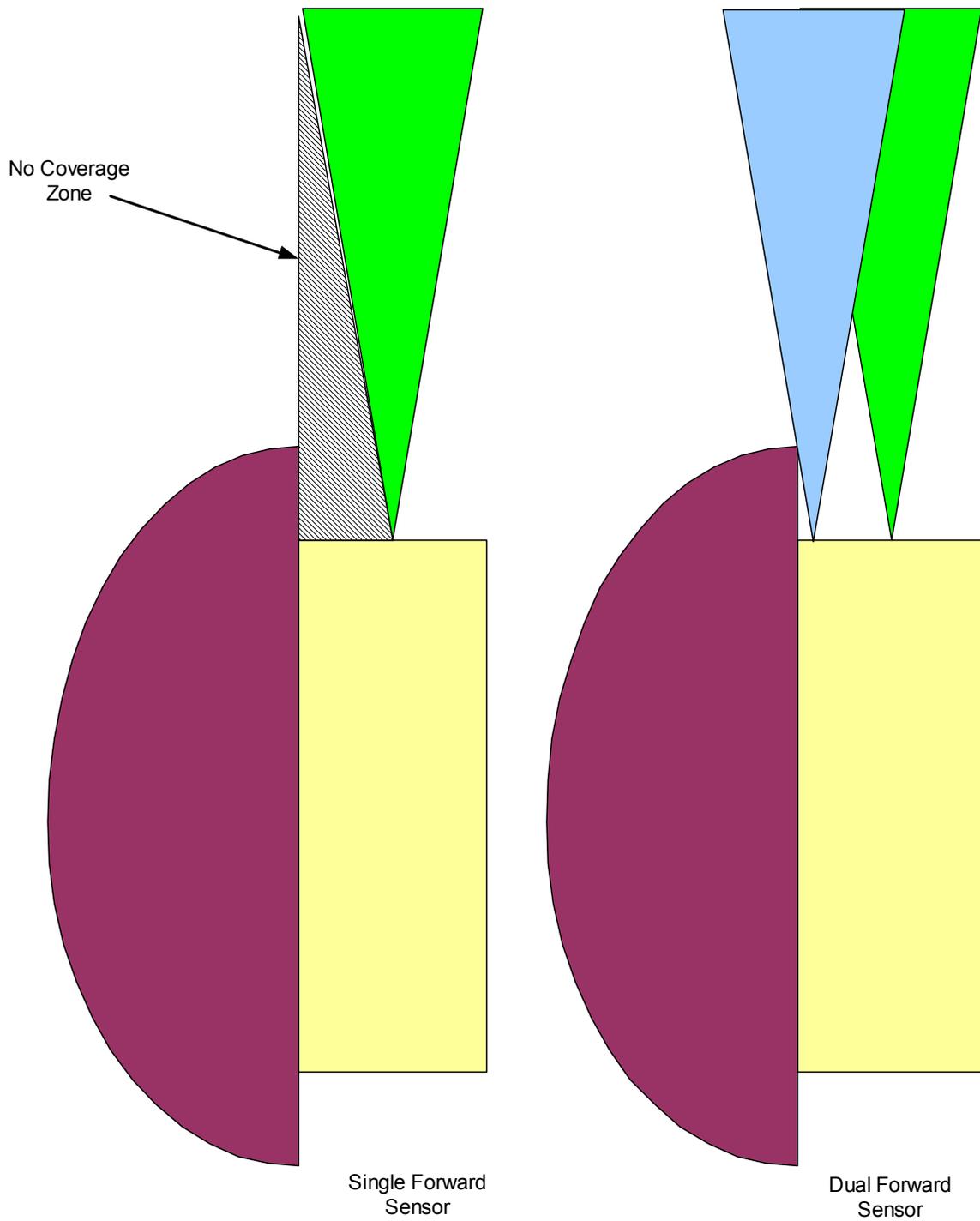


Figure 22. Radar coverage areas for single and dual forward looking radar. Purple indicates the practical effective range of the scanning Lidar sensor. On the left drawing, the cross-hatched area represents the area for which no obstacle detection exists; right drawing illustrates improvement of sensor coverage with addition of second EVT-300 radar.

Forward obstacle detection information is presented to the driver through the HUD as shown in Picture 3. As indicated in the caption, square boxes indicate forward radar targets. Radar is able to inform a driver that *something* is ahead and where it is, but it is unable to inform a driver *what* that something is. Because of this ambiguity, the HUD displays an icon to represent a legitimate forward obstacle.

How this icon is presented requires some discussion. First, the radar sensor provides range, range rate, and azimuth angle to the target. Within the resolution capabilities of the radar, this allows the position of the obstacle with respect to the host vehicle to be precisely known. The relative position of the obstacle is then projected onto the HUD with the proper perspective. If the obstacle ahead of the host vehicle changes lanes, the target is tracked, and the icon “changes lanes” as well. If the obstacle slows and approaches the host vehicle, the icon becomes larger, consuming more of the field of view of the HUD, consuming more of a driver’s attention. This behavior is identical to that experienced by a driver following another vehicle during good visibility conditions. The only missing piece of data is the information as to the type of vehicle detected.

Virtual Mirror.

The virtual mirror is covered in detail in Volume II of this report.

Chapter 8. Partnership Development

The purpose of this task was to work with Metro Transit to develop partnerships which would build on the results of this project to further the development of lane assist systems.

In June of 2001, the Federal Transit Administration announced an RFP for a phase one study of lane assist technology for Bus Rapid Transit applications. Metro Transit and the University of Minnesota ITS Institute, IV Lab, and the HumanFirst program developed a proposal which was submitted to the FTA. The proposal was accepted by the FTA, and a contract was awarded to Metro Transit, with the University of Minnesota as its partner. The FTA contract was worth \$400,000; Metro Transit provided \$100,000 in cost share, enabling the partnership to meet its 80/20% requirement. Approximately \$35,000 in cash from Metro Transit was used to purchase the electronic and computer equipment used on the Technobus.

As a result of this partnership, a two-volume report on the technological and human factors issues associated with lane guidance systems were produced (see [9] and [10]). Successful completion of this project should well position the Metro Transit / University of Minnesota team to compete for the phase two FTA RFP which is expected to be announced in the Fall of 2003.

Other potential projects are being identified. In late July 2003, New Flyer bus, the supplier of articulated buses to Metro Transit and a company with manufacturing plants in Crookston and St. Cloud, Minnesota, visited the IV Lab to investigate the possibility of adapting IV Lab lane assist technology into their new BRT ready bus. Discussions regarding the implementation of the IV Lab technology on a wider basis continue.

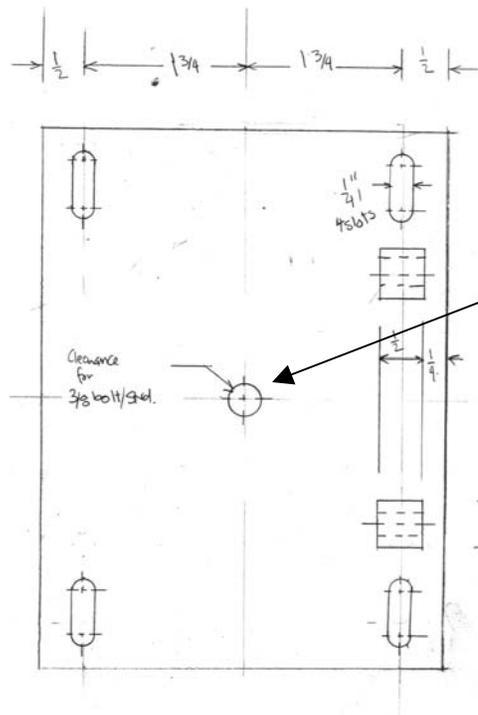
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- [3] Michael Sergi, Bryan Newstrom, Alec Gorjestani, Craig Shankwitz, and Max Donath, “Dynamic Evaluation of High Accuracy Differential GPS,” Proceedings of the ION National Technical Meeting, Anaheim, pp 581 – 592, 2003.
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- [7] “Populating Geospatial Road Database” Inventors: Bryan Newstrom, Craig Shankwitz, Max Donath, Patent Filed July 2002.
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- [9] Craig Shankwitz, Lee Alexander, Alec Gorjestani, Pi-Ming Cheng, Bryan Newstrom and Max Donath, “Bus Rapid Transit Lane Assist Technology Systems, Volume 1: Technology Assessment,” Report submitted to the FTA, July 2003.
- [10] Nicholas J. Ward, Alec Gorjestani, Craig Shankwitz, and Max Donath, “Bus Rapid Transit Lane Assist Technology Systems, Volume 2: Bus Driver Stress While Operating in Narrow Dedicated Bus Shoulders: A Pilot Study,” Report submitted to the FTA, July 2003.

Appendix A. Steering Actuator Hardware Design

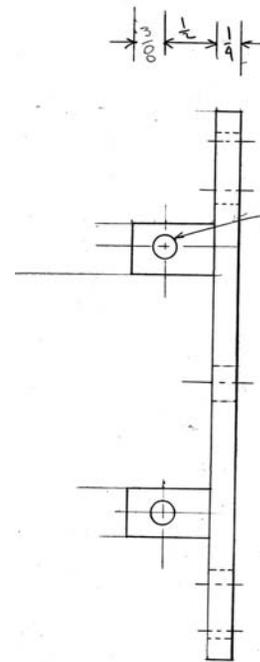
The steering actuator design is based around a Kollmorgen servo motor. The steering actuation system consists of a Kollmorgen servomotor (model MT-308A1-R1C1), a Kollmorgen servo amplifier (model number CR-03250-0000) and cable assembly (model CS-SS-RHAIHE-06). Power transmission from the servomotor to the steering mechanism is via a toothed belt / pulley mechanism, with a 3:1 speed reduction from the motor to the steering shaft. Power transmission parts were sourced from Gates using Polychain components. System feedback is provided by a “semi-absolute” encoder mounted in the end of the servomotor. Semi-absolute in this situation means that the encoder is absolute upon power up, using its power-up position as “zero.” On power down, that “zero” is “forgotten”, and a new “zero” is designated the next time the system is powered.

The steering actuator is connected to the Technobus via the equipment described below. The steering actuator motor mounting plate shown in Figure A-1 bolts to the steering structure on the bus. The steering motor bracket shown in Figure A-2 supports the motor and maintains parallelism between the motor drive and the steering shaft driven pulleys. The T-Link shown in Figure A-3 acts as the interface between the steering actuator motor mounting plate and the steering motor bracket. The steering motor bracket slides along the T-Link, allowing the tension in the Gates polychain to be maintained at approximately 10 pounds force.



T-Link
attaches at
this point.

Front View



Dr. Hole Top of
1/4 x 20 TPI
ALL 1020 steel

Side View

Figure A 1. Steering actuator motor mounting plate. This plate bolts to the steering column structure, and supports the steering motor which is mounted onto the steering motor bracket.

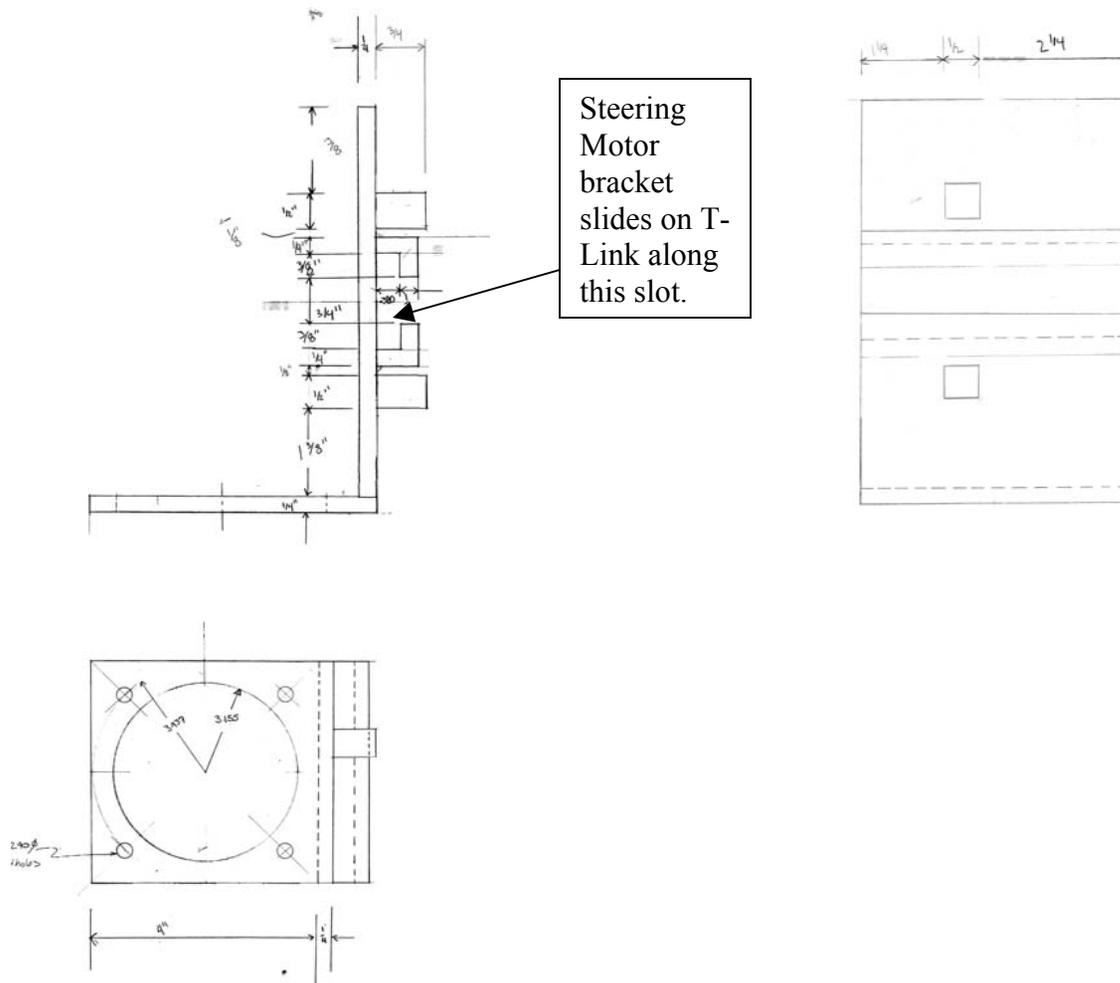


Figure A 2. Steering Motor bracket. This bracket supports the Kollmorgen Servo motor used to actuate the steering, and mounts to the steering motor actuator plate via the T-Link.

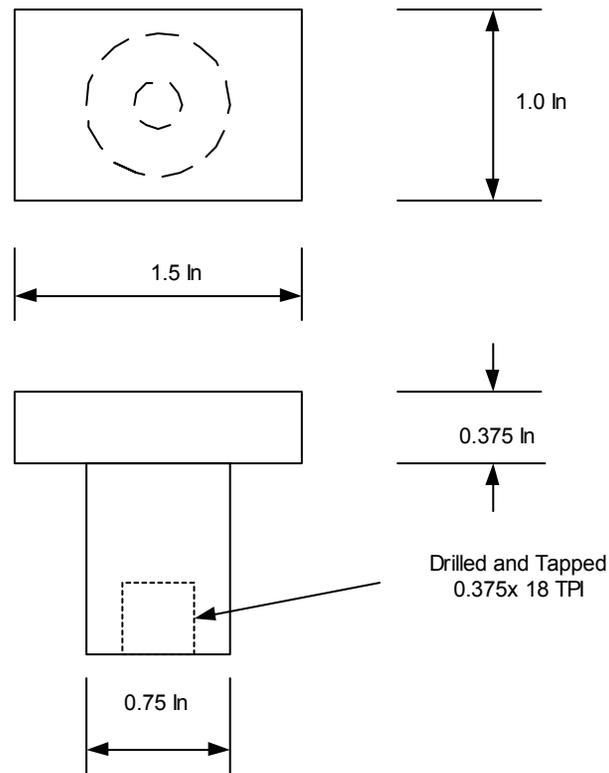


Figure A 3. T-Link connects the steering motor bracket to the steering motor actuator plate. The T-Link Steering Motor is bolted to the steering actuator motor mounting plate as indicated in Figure A-1 above. The steering motor bracket slides on the T-Link as indicated in Figure A-2 above.

Appendix B. Failure Modes and Effects Analysis

Twin Cities Metro Transit provided the Technobus to support the research efforts of the IV Lab. Metro Transit provides fuel, drivers, maintenance, and storage for the Technobus at the Heywood Transit Facility.

The research and development undertaken could be considered to put drivers and passengers at a higher risk than that to which general transit passengers and drivers are subject. The addition of a steering actuator to the standard bus steering gear is a significant modification to the standard transit bus steering mechanism. Clearly, a failure of the steering system which prevents the steered wheels from being pointed as intended puts the driver and passenger at risk.

To quantify the risk associated with the development of a driver assistive system for a transit bus, a Failure Modes and Effects Analysis was performed for the steering system. The FMEA was based on the FTA document DOT-FTA-MA-26-5005-00-01; specifically, the FMEA worksheet as shown on page 19, “Hazard Analysis Guidelines for Transit Projects” was completed.

Included in this Appendix is a copy of the memo sent to Metro Transit summarizing the results of the FMEA analysis and a copy of the FMEA worksheet described above.

Memo

**TO: Steve McLaird
Metro Transit**

**FROM: Craig Shankwitz
Intelligent Vehicles Lab**

DATE: 25 June 2002

SUBJECT: Failure Modes and Effects Analysis for Technobus

Per our phone conversation of 19 June 2002, I have completed the FMEA worksheet as shown on page 19, "Failure Modes and Effect Analysis (FMEA) Form," of FTA Document DOT-FTA-MA-26-5005-00-01, "Hazard Analysis Guidelines for Transit Projects." Included in this memo is the completed form, and some supporting data from Kollmorgen, the manufacturer of both the servo-amplifier and servo-motor used in the steering motor application.

A few comments are warranted regarding the design of this system. From the results of the safety review of the bus system held after the APTA conference, Metro Transit's main concerns regarding the design of the steering actuator were focused on the hard mechanical failure of the motor and/or motor bearings which would prevent the steering wheel from turning. Clearly, the inability of a driver to steer the bus is a serious condition, and one which should be avoided.

The use of the Kollmorgen servo system represents a very conservative design. In the bus, this motor is unlikely to see any rotational speeds in excess of 300 RPM. Because of the Gates Polychain belt used to connect the motor to the steering shaft, belt tension can be kept low, at approximately 10 lbs, placing a total radial load on the motor of 20 pounds. (Because of the motor mount design, motor axial loading can be eliminated). Using the Kollmorgen provided L10¹ data, we can expect nearly infinite life from the servo motor bearings.

Bearing failure would increase the frictional loads at the motor, causing a constant torque output of the motor to require increased current to be provided by the servo motor. The Kollmorgen system includes both current and temperature monitoring as a means to monitor for bearing and motor failure. This will be done as part of this design.

¹ L10 is defined by the Anti-Friction Bearing Manufacturers Association as the radial load at which a 90% of a group of identical ball bearings will exhibit a service life of at least one a million revolutions.

Concern regarding the failure of the armature or field windings was also expressed during the safety review. The Kollmorgen servo motor has been designed for severe usage. The question of ruggedness of the motor was posed to Kollmorgen; their response regarding the likelihood of the motor failing is provided below:

“the only common failure mode would be bearing failure. In fact in the XT family of motors from Kollmorgen the windings, which are in the stator (non moving outside) are potted in epoxy so they can't move.

The magnets are in the rotor (the moving part). They are completely surrounded by steel (buried magnet design). They are not glued on so a sharp blow will not loosen them.”

The Intelligent Vehicles Lab's research vehicle SAFELOW has used the same servo-amplifier and a servo-motor (but with higher torque capacity) from the same Kollmorgen family since 1999 without any amplifier or motor failures. However, unlike the TechnoBus, the SAFELOW servo-motor is located outside of the vehicle cab, exposed to the elements, and severe abuse, including snowplow operations. On the TechnoBus, the motor is protected from road spray, washdown spray, and deicing elements.

Finally, the issue of the motor overpowering the intentions of the driver was raised. A number of actions have been taken to prevent this from occurring. First, as a set-up parameter, the maximum current to be delivered to the steering motor can be limited. This is equivalent to limiting motor torque. Second, the torque motor actuating the steering system has a maximum deliverable torque. Even at maximum rated torque, a driver can overdrive the steering torque provided by the motor. Third, an emergency stop is provided at the driver's left hand. Should he or she not like the feedback provided by the steering motor, the e-stop can be hit, killing power to the torque motor, and allowing the bus to be driven as normal.

I hope that this document represents a sufficient FMEA report. Please feel free to call me with questions or comments regarding this document.

| General Description | | | Hazard Cause/Effect | | | Corrective Action | |
|--------------------------|--|--|--|--|--|---|--|
| LRU No. & Description | Failure Mode | Cause of Failure | Effect of Failure on Subsystem/System | Probability of Occurrence ² | Severity of Occurrence | Possible Controlling Measures and Remarks | Resolution |
| Steering System actuator | Servo motor amplifier failure | Loss of power to amplifier, blown fuse, wiring failure | Active guidance assistance lost, return to manual steering | 1x10 ⁻⁴ | Negligible if following bus-only-shoulder rules, marginal if exceeding rules | Drivers following bus only shoulders rules of engagement | Driver Training, Servo amplifier supply wire gage size larger than necessary |
| Steering System actuator | Servo motor amplifier failure | Circuit/interface/Power supply failure | Active guidance assistance lost, return to manual steering | 1x10 ⁻⁵ | Negligible if following bus-only-shoulder rules, marginal if exceeding rules | Controller capacity in excess of motor capacity, minimizes thermal load on motor amplifier | Driver Training, Conservative amplifier for load service |
| Steering System actuator | Servo motor supplying excessive current (excessive motor torque) | Software bug | Steering wheel attempts to go "hard over" | 1x10 ⁻⁴ | Marginal if bus driver attentive, critical if driver inattentive | Limit torque capacity of system, thereby limiting the rate at which the steering wheel can rotate Hitting "E-stop" kills power to servo motor. | Limit of current output capacity of servo amplifier Use small torque output motor |
| | | | | | | | |

² Per FTA document DOT-FTA-MA-26-5005-00-01, measured in events per million hours of operation. These are estimates based on SAFEFLOW experience.

| General Description | | | Hazard Cause/Effect | | Corrective Action | | |
|--------------------------|--|--|---|---------------------------|--|---|---|
| LRU No. & Description | Failure Mode | Cause of Failure | Effect of Failure on Subsystem/ System | Probability of Occurrence | Severity of Occurrence | Possible Controlling Measures and Remarks | Resolution |
| Steering System actuator | Servo motor supplying excessive current (excessive motor torque) | Control computer failure | Steering wheel attempts to go "hard over" | 1×10^{-4} | Marginal if bus driver attentive, critical if driver inattentive | Limit torque capacity of system, thereby limiting the rate at which the steering wheel can rotate Hitting "E-stop" kills power to servo motor. | Limit of current output capacity of servo amplifier Use small torque output motor |
| Steering System actuator | Servo motor supplying excessive current (excessive motor torque) | Feedback sensor failure | Steering wheel attempts to go "hard over" | 1×10^{-6} | Marginal if bus driver attentive, critical if driver inattentive | Limit torque capacity of system, thereby limiting the rate at which the steering wheel can rotate Hitting "E-stop" kills power to servo motor. | Limit of current output capacity of servo amplifier Use small torque output motor Optical encoders extremely reliable |
| Steering System actuator | Belt Breakage | Excessive motor torque | Active guidance assistance lost, return to manual steering | 1×10^{-6} | Marginal if bus driver attentive, critical if driver inattentive | Limit torque capacity of system, thereby limiting the rate at which the steering wheel can rotate | Belt is oversized for application Periodic inspection of belt |
| Steering System actuator | Foreign object falling between pulley and belt | Inability to run steering wheel one particular direction | Ability to turn bus in that particular direction lost, loss of vehicle steering control | 1×10^{-5} | Marginal if bus driver attentive, critical if inattentive | Keep foreign objects from entering beltway | Guard designed and built, will be installed on bus |

| General Description | | | Hazard Cause/Effect | | | Corrective Action | |
|--------------------------|-----------------------|--|---|---------------------------|--|--|---|
| LRU No. & Description | Failure Mode | Cause of Failure | Effect of Failure on Subsystem/ System | Probability of Occurrence | Severity of Occurrence | Possible Controlling Measures and Remarks | Resolution |
| Steering System actuator | Motor bearing failure | Excessive load on bearing, life cycle of bearing | <p>Increased resistance to manual steering input, increased current from servo motor to achieve constant motor torque output</p> <p>Sudden failure could prevent motor from turning, thereby keeping steering wheel from turning.</p> | 1x10 ⁻⁷ | Negligible with gradual wear, critical with sudden bearing failure | Limit radial and axial loading on motor bearings, chosen motor comes with oversized motor bearings | <p>Radial, axial, and thrust loads on bearings less than design spec.</p> <p>Motor bearings are designed for 10 years at max continuous torque and 9 years at max operating temp.</p> <p>Monitor current draws and motor temp, detect trends</p> <p>Keep motor inside of the bus, limiting exposure to corrosive environment.</p> |
| Steering System actuator | Motor shaft failure | Excessive load on shaft | Active guidance assistance lost, return to manual steering | 1x10 ⁻⁸ | Negligible if following bus-only-shoulder rules, marginal if exceeding rules | Drivers following bus only shoulders rules of engagement | Motor shaft loading less than 5% of (plastic) bending load |

| General Description | | | Hazard Cause/Effect | | | Corrective Action | |
|--------------------------|-------------------------------------|--|---|---------------------------|------------------------|--|--|
| LRU No. & Description | Failure Mode | Cause of Failure | Effect of Failure on Subsystem/ System | Probability of Occurrence | Severity of Occurrence | Possible Controlling Measures and Remarks | Resolution |
| Steering System actuator | Armature failure (comes apart) | Excessive motor speed, excessive motor heating | Binding of steering system, preventing rotation of the steering wheel | 1×10^{-8} | Critical | motor designed for 1000's of RPM. On steering shaft, motor runs 10's of RPMs | Motor speed kept low Permanent magnet motor design chosen. Magnets embedded in laminated steel armature. If magnet comes apart, it cannot escape steel surround |
| Steering System actuator | Field winding failure (comes apart) | excessive motor heating, excessive motor vibration | Binding of steering system, preventing rotation of the steering wheel | 1×10^{-8} | Critical | motor designed for 1000's of RPM. On steering shaft, motor runs 10's of RPMs | Current to motor limited, keeping heating low. Field windings wound on steel stator, proving high fatigue life. |