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Wei-Bin Zhang, Steven Shladover, Douglas Cooper, Joanne Chang, Mark Miller, Ching-Yao Chan, and Fanping Bu

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Abstract

This report defines the transit service needs that can be met by use of lane assistance systems and the requirements that these systems must meet in order to be useful and safe. The work is based on review of the existing literature and research on the subject of lane assistance, combined with case studies of several transit properties that could potentially benefit from use of lane assist systems. The project team has conducted workshops involving participation by a broad mix of people representing the transit properties in order to learn about the needs that they perceive, as well as both benefits and risks that they perceive associated with use of lane assist technology. Because these transit properties are significantly different from each other, their needs are also diverse.

Keywords: Vehicle Highway Automation, Lane assist, electronic guidance, Bus Rapid Transit, precision docking, automatic steering

Executive Summary

This report defines the transit service needs that can be met by use of electronic guidance systems and the requirements that these systems must meet in order to be useful and safe. Guidance system functions include automatic steering of buses driving between stations (lane assist) and automatic precision docking of buses at stations. These functions can be implemented using a variety of sensing and reference technologies, but those technologies are not the primary focus of the work here. Rather, this report addresses issues that are essentially independent of the chosen technology.

The work is based on review of the existing literature and research on electronic guidance, combined with case studies of several transit properties that could potentially benefit from use of electronic guidance systems (Lane Transit District of Eugene, OR, AC Transit of the Oakland/East Bay region of northern California, Los Angeles County Metropolitan Transit Agency and San Diego Association of Governments). The project team has conducted workshops involving participation by a broad mix of people representing these transit properties in order to learn about the needs that they perceive, as well as both benefits and risks that they perceive associated with use of electronic guidance. The work has been based on the concept that it is necessary to understand the perspectives of not only the transit operating agencies, but also of the bus drivers and the passengers, since it will be important to have acceptance and support from all of them.

The report begins with a basic introduction to electronic guidance systems, including project background, a summary of the candidate technological implementations, and the relationship of the guidance system to the typical work of the bus driver. This raises a variety of important issues that need to be considered in the design of any guidance system:

- maintaining an appropriate level of driver workload
- reducing driver stress, particularly by ensuring high system reliability
- clarifying roles of the driver relative to the system
- carefully designing control transitions between driver and system.

Potential application environments for electronic guidance are described as new median bus lanes, restriped bus lanes, narrow bridges, tunnels or toll booths, and new dedicated busways. The technologies that could be used to provide guidance information are classified as mechanical (curb contact), computer vision, permanent magnets, current-carrying wires, and GPS satellite navigation systems. Their general advantages and disadvantages are described qualitatively.

Section 2 collects the inputs that were derived from site-specific case studies for four transit properties at different stages of maturity in their consideration of electronic guidance for their BRT systems, including workshops conducted at all four properties. Lane Transit District (LTD) is the most mature, having already seriously considered adding guidance capabilities to the BRT system that they are introducing to the public in late 2006. AC Transit is not as far along in the process, proceeding with the environmental documentation for their new BRT system assuming that it will not include guidance capabilities, but willing to consider adding it if it appears to be sufficiently advantageous. Although Los Angeles County MTA already has an extensive BRT system, they have not been seriously considering guidance applications until now. SANDAG is still in the early stages of thinking about their BRT service and has not yet actively considered guidance capabilities. Section 2 is organized by the issues that cut across all four properties: specific applications, qualitative benefits and costs, system requirements, design features and institutional challenges to deployment.

The LTD case study highlighted many of the important issues for electronic guidance systems from the perspective of an operator that has already been thinking seriously about the issues. They are primarily interested in electronic guidance for facilitating narrower track and right of way on the exclusive busway parts of their network and for precision docking to facilitate disabled access. Their concerns about electronic guidance revolved around issues of liability, driver engagement, control transitions, maintenance of vehicle systems (ensuring service intervals comparable to other bus subsystems), and maintenance of infrastructure. Other important issues specific to driver interfaces involved the need for training to address both normal and abnormal conditions, a DVI that provides useful feedback about the status of the system, and the constraints imposed by a state law requiring that the driver’s hands always be on the steering wheel.

AC Transit was interested in several different applications of guidance capabilities – precision docking on their existing Rapid line, lane assist on a new BRT service that will operate in the roadway median, automation of bus maintenance facility and yard operations, and maintaining speed while driving through a toll booth with narrow lateral clearance. Their interest in precision docking is motivated by a high percentage of disabled riders and the potential that enhanced accessibility of their mainline bus services could reduce the need to provide costly para-transit services to disabled riders. With precision docking, they would hope to be able to save enough time at bus stations that they could eliminate the cost of running an additional bus or buses while providing the same level of service. The lane assist function could enable them to save width of their new BRT busway, thereby reducing costs and neighborhood concerns about loss of on-street parking and could also provide a more rail-like smoothness of ride. Bundling this with other advanced technology features such as forward collision warning and adaptive cruise control could lead to smoother accelerations and decelerations, thereby reducing passenger falls. Their concerns involve practical considerations of system durability when operated over the long term on rough pavement surfaces.

Los Angeles County MTA would be interested in seeing a large-scale demonstration of electronic guidance capabilities on a closed test track before committing to deployment on their buses. Their priority considerations are system safety, reliability and consistency of performance. The potential benefits they could envision are focused primarily on time savings through station dwell time reductions and higher speeds in narrow lanes. They have a variety of concerns that must be addressed, including the need for liability indemnification from the system supplier, the potential for drivers to demand higher pay based on any additional skills or training required to operate the system, worries about the engineering work needed to design and implement the docking profile for each bus station, and worries about the ability of the system to accommodate road surface imperfections beyond their control (poorly maintained and severely crowned surfaces).

The key issues were addressed in a joint workshop held with representatives of the participating transit properties to discuss and compare their requirements and needs. This workshop brought forward the difficulty of defining a single uniform set of requirements for all lane assist systems, since each property expressed different needs and priorities. This is one of the primary challenges to the development of these systems. The categories of issues that were covered included system performance (lane tracking and docking accuracy, ride quality), infrastructure changes needed, reliability and robustness, maintenance of vehicle and infrastructure elements of the system, availability, driver acceptance (primarily fault handling), safety, public and passenger acceptance, and costs. The most compelling benefit argument for the lane assist functions was the ability to save enough time on the bus route that a bus could be eliminated from operations while maintaining the same service (operating headway).

Section 3 includes more detailed quantitative analyses of system benefits and costs. The potential benefits of electronic guidance systems are introduced in qualitative terms, in the categories of:

- providing rail-like image and service quality
- reducing driver stress
- reducing infrastructure construction and right of way cost by narrowing lanes
- saving stop time at bus stations
- providing enhanced accessibility to elderly and disabled passengers
- improving safety by reducing driver errors
- reducing paved surface area for exclusive busways.

Preliminary economic evaluations of electronic guidance systems in Section 3.2 focus on the time savings from precision docking and the lane width savings from automatic steering. These analyses are sensitive to the costs for equipping each bus, which were assumed to be $100 K for small numbers of buses in the very near term, $14 K per bus when produced in quantities of hundreds of buses per year, and $2.7 K per bus when produced in quantities of thousands of vehicles per year in the future. The docking analyses sought to identify the break-even points in station dwell time reduction where the costs of the system would be matched by the savings in bus operating costs. These ranged from 4.2 seconds per stop for Lane County to 12.3 seconds per stop for Los Angeles (where the study considered only a short section of three stops on their Metro Rapid service, but would still have required equipping all the buses operating that service). The automatic steering analyses sought to identify the break-even busway construction costs where the costs of the lane assist system would be matched by the reduction in surface area needed for narrower lanes. These ranged from $15.35 per square foot for Lane County to $38.67 per square foot for Los Angeles.

The potential safety benefits of electronic guidance systems are addressed in Section 3.3, based on a review of existing actuarial data on bus safety problems and consideration of how the scenarios and maneuvers associated with those problems (collisions and other incidents leading to insurance claims) would change with use of guidance systems. The safety improvements are expected to be associated with reducing passenger boarding and alighting problems, reducing passenger falls, and improving drivers' focus on hazards in the driving environment so that they can avoid some collisions.

Section 4 provides the system requirements, specifications, measures of effectiveness and a preliminary example system safety analysis. This begins with a functional decomposition and generic system architecture. The architecture begins at the logical level, then proceeds to a physical architecture, independent of technology.

The categories of relevant functional requirements are identified as:

- safety
- performance (ride comfort, accuracy, ease of operation)
- reliability
- availability
- maintenance ease and cost
- compatibility with existing infrastructure.

These are closely related to the measures of effectiveness needed to evaluate different guidance system design alternatives:

- safety
- operational improvements (time savings, ride quality)
- reliability
- availability
- capital costs
- operating and maintenance costs and other needs imposed on the agency
- weather limitations
- infrastructure impacts
- public perception
- driver acceptance.

Section 4.3 of the report introduces draft specifications and requirements for electronic guidance systems. These begin at the level of system performance, addressing issues such as accuracy of lane keeping and position indications to the driver, driver display (DVI) contents, acceptable weather conditions for operation, ride quality, and control transitions. Subsystem requirements include issues such as position sensing capabilities (coverage, accuracy, resolution, update rate, environmental robustness), actuator performance, and DVI characteristics. Infrastructure requirements and driver training and maintenance requirements are also addressed.

The safety analyses begin with a preliminary hazard analysis, then a determination of safety integrity level, based on the probability and severity of the identified hazards. These hazards include environmental factors, driver actions, passenger actions, component failures and design errors. Finally, a failure mode effects and criticality analysis (FMECA) is presented, based on the specified functions and individual failure modes for each function

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1.0 INTRODUCTION

Bus Rapid Transit (BRT) systems can provide high quality, high capacity bus transit service on easily identifiable route structures at a cost lower than that of urban light rail systems. They may apply integrated land use planning and advanced design concepts, as well as intelligent transportation systems (ITS) concepts and technologies, to provide significantly higher operating speeds, greater service reliability, and increased convenience. BRT can thereby become a cost-effective alternative to urban light rail systems, with the potential to attract non-traditional riders and contribute to the reduction of traffic congestion. Many regions in the United States are very interested in planning for and deploying BRT. Although each of the BRT deployment sites has unique features, all BRT-interested agencies are commonly interested in applying advanced operational concepts and technologies, particularly Intelligent Transportation Systems (ITS) technologies that can improve efficiency, safety and service level of BRT operation. BRT interested agencies have expressed strong interest in incorporating electronic guidance technologies.

Electronic guidance can be applied to transit buses to provide lane assist and precision docking functions. Lane assist allows the bus to operate in a designated lane that is only inches wider than the bus itself, while precision docking enables buses to precisely stop at bus stations without increasing driver workload. Electronic guidance can be implemented with partially or fully-automated modes to guide buses through narrow bridges, tunnels, toll booths, and roadways, as well as bus stops, tight curves, and designated trajectories in maintenance yards. The precision docking capability at bus stops, which allows fast loading and unloading of passengers with special needs, thereby reduces station dwell time.

Electronic guidance technologies provide numerous ‘rail-like’ features that enhance efficiency, safety and quality of service for the BRT operations. They may become critical components of a BRT design when the space for the planned BRT lane is constrained. Electronic guidance may also be considered as an option to augment the initial BRT design, where this option is not essential but could provide significant performance improvements. Lane assist systems can be implemented in mixed traffic lanes, which the bus shares with normal traffic, or in dedicated bus-only lanes, which could be separated from the other lanes by road markings or by physical structures (barriers).

The deployment of lane assist systems can be viewed from three perspectives: that of the transit agency, the transit driver, and the transit passenger. For the agency, lane assist systems offer significant benefits including the delivery of rail-like service, an attractive feature to riders, at a fraction of rail cost. From the driver’s perspective, the lane assist system can be a means to decrease workload and stress while at the same time allowing him/her to operate in more challenging environments (e.g., narrower lanes). For passengers, the implementation of an electronic guidance system will mean smoother operation, faster and safer boarding and alighting, better schedule reliability, and increased mobility for ADA riders.

1.1 Project Background

Under the sponsorship of FTA, the Minneapolis-Saint Paul Metropolitan Transit Agency (Metro) and University of Minnesota ITS Institute developed requirement specifications for a lane assist system. FTA also requested a separate effort led by the California Department of Transportation (Caltrans) to develop inputs on system needs and requirements. In response to FTA's request, AC Transit, Los Angeles County Metropolitan Transportation Authority (LACMTA), Lane County Transit District (LTD), and San Diego Association of Governments (Sandag), the California Department of Transportation (Caltrans), Gillig Corporation and California PATH Program (PATH) formed a partnership to support and supplement the Metro team's work in developing requirements and specifications for transit lane assist and precision docking systems.

System requirements stem from stakeholder needs. AC Transit, LACMTA, and LTD are all members of the BRT Consortium. These agencies have planned dedicated BRT routes and are convinced that electronic guidance technologies can offer benefits in enhancing the efficiency, safety and quality of BRT service. This report examines the needs for and potential applications of lane assist and precision docking systems for these BRT sites. Through the case studies, this project has (1) defined transit agency needs for lane assist technologies and (2) defined both performance requirements and technical specifications for lane assist and precision docking systems. As such, the emphasis of this project has been placed on receiving inputs from partner transit agencies through workshops and close interactions. The case studies of the BRT sites have addressed the following issues:

- Needs, functionalities, and applications of lane assist systems
- Cost-benefit analysis of lane assist systems and their specific types of benefits (and potential synergies with other advanced technologies)
- Drivers' perspectives on lane assist systems
- Operation environment and conditions, including constraints
- Maintenance aspects of lane assist systems.

The synthesized inputs from the transit agencies captured the common and special needs, benefits and constraints of each type of application for the transit lane assist and precision docking systems. Based on the stakeholders' inputs, in-depth studies on benefits and costs have been conducted. The stakeholder perspectives also provided qualitative requirements, which have been translated into system definitions, performance requirements and technical specifications.

1.2 Technology Options

Electronic guidance technologies are designed to aid the driver in controlling vehicle position within designated bus lanes (lane keeping or lane assist) or to follow a specific trajectory when coming to a stop (precision docking). When engaged, lane assist systems are designed to perform these functions without driver input, although they may also be designed to provide "assist" functions that augment a driver's steering actions to provide more accurate lane keeping performance. In either case, systems applying electronic guidance technologies are necessary to maintain safety because of the smaller margin for error associated with operating a bus in narrower lanes, especially adjacent to regular traffic.

Assisted guidance has been in development for the past thirty years. What differentiates the various technologies is their means of position sensing. Most have been thoroughly tested in the research phase and their advantages and disadvantages assessed. The appropriateness of each of these technologies is likely to depend heavily on the circumstances associated with the particular BRT operation being considered.

Lane assist systems can be classified as either mechanical or electronic, depending on how the lane deviation and correction are performed. The Metro team has conducted a technology review and the results were reported in [Donath et al., 2003[1]]. Under this project, a scanning tour with participation of FTA, FHWA, transit agencies and PATH was conducted to collect information from several European organizations that have had experience in the development and operation of transit lane assist systems based on three different technologies, including (1) optical guidance in Rouen, France, (2) magnetic guidance in Eindhoven, Netherlands and (3) mechanical guidance in Essen, Germany. Findings were documented in [Shladover, et al, 2005[2]]. The following provides a high-level overview of the electronic guidance technologies reviewed by these two studies and a summary of the advantages and disadvantages of each technology.

1.2.1 Mechanical Guidance

Mechanical guidance relies on physical contact between the vehicle and the infrastructure. Location of the vehicle relative to the roadway is determined via changes in the nature of this physical contact. An example of this type of system is used in Essen, Germany, where each bus is fitted with special "guide wheels" by the front wheels, allowing the bus to transfer from a road onto the track in one smooth, easy movement. The guide wheels are directly connected to the vehicle's steering mechanism and once these guide wheels are locked in place, the track is effectively steering the bus. Another type (e.g., in Nancy, France) utilizes central guide wheels which are in contact with an underground guide rail in a slot in the middle of the bus lane.

Figure 1.1 Mechanical Guide wheel on bus in Essen, Germany

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[1] Adapted from Minneapolis Metro Transit and the University of Minnesota ITS Institute (February 2003), Bus Rapid Transit Lane Assist Technology Systems Volume 1: Technology Assessment, Minneapolis, MN

[2] California PATH, et. al., Lane Assist Systems in Europe: Report on Technical Visit to Europe on Transit Lane Assist Technologies

Advantages of mechanical guidance technologies

- High reliability – often very low tech, direct mechanical linkages can be employed to ensure high reliability under all kinds of conditions.
- Very high positional accuracy.
- Relatively low per vehicle cost – mechanical sensing systems may be less expensive than electro-optical sensing.
- Because the systems are mechanical with exposed parts, visual and manual inspection is straightforward and can be performed at the beginning of each driver's shift.
- These systems are relatively insensitive to weather and other environmental conditions; however, ice jamming of the buried guidance rail can be a problem.
- Finally, in the (rare) event of a system failure, a busway, with vertical curbs provides a physical means with which to keep the bus out of adjacent lanes, keeping the passengers and motorists in the adjacent lanes safe.

Disadvantages of mechanical guidance systems

- Often requires a dedicated lane leading to potentially high infrastructure modification costs. This will depend heavily on the type of infrastructure required and the infrastructure already in place or planned for the BRT site. A transit agency whose right-of–way is extremely limited may be forced to eliminate this system from consideration.
- Potential impediments to other vehicle traffic. Some types of infrastructure modifications to support mechanical guidance, (e.g. rails) may preclude the use of the lanes by other traffic. In a dedicated lane scenario this should not be a problem. This system would negate use of lanes by emergency vehicles.
- Sensitivity to vehicle failure – A breakdown of a bus on a narrow, hard-barrier separated narrow lane could result in a system-wide shutdown since the disabled bus will not be easy to move. Diverting other automated buses around the bottleneck would be difficult since lane "jumping" is precluded by the barriers.
- It is difficult to design a fixed feedback mechanical mechanism that can meet performance requirements under different operating conditions. Transition between guided and unguided areas, for example, may not be smooth if not properly designed (http://www.lightrailnow.org/features/f_ncy001.htm)
- The tight physical tolerances on the construction of the mechanical guiderails lead to high infrastructure costs, virtually as high as for light rail in the case of Essen.

1.2.2 Electronic Guidance

Electronic guidance systems use sensors to detect a vehicle's lateral deviation from the lane center. This deviation is then fed back to a computer where a corrective steering command is calculated and sent to a steering actuator which will steer the vehicle back to the center in order to maintain the vehicle within lane boundaries. Determining the vehicle's lateral deviation with high accuracy, high bandwidth and robustness is very important to the successful implementation of electronic guidance.

1.2.2.1 Vision-based Guidance

Vision-based guidance systems use optical methods to determine the vehicle's location relative to the lane by the sensing of features such as lane markings. This optically derived information is used to provide lateral control assistance to the driver. Optical sensors can vary in their sensing technology (passive vs. active) and their orientation (forward looking vs. downward looking). Optical sensors include traditional video cameras as well as infrared (IR) cameras.

General advantages of optical technologies

Typically fewer infrastructure modifications are required since they can sometimes work with existing lane markings or other road features. Because of their flexibility and relatively minor infrastructure needs, optical technologies can provide benefits beyond the specific narrow lanes where control assistance for the driver is required. This will be particularly useful in BRT scenarios where buses need to leave the narrow designated travel lanes and travel on normal roads. This extended functionality could include lane assistance similar to that available on the narrow lanes or passive warnings/advisories directed toward the driver. Such flexibility will allow for easy diversion from a typical route if conditions require (e.g. breakdown of another bus on narrow lane).

Optical technologies may also be employed to support other functions that may be important for a BRT system, including precision docking, longitudinal (headway) control, pedestrian detection, and sign recognition. Other advantages include:

- Position accuracy – This is particularly possible with downward looking passive or active systems.
- Small size – Optical sensors are usually small, sometimes down to one cubic inch. This makes packaging, installation and maintenance relatively easy, and does not detract from the appearance of the bus.
- While components will tend to be higher cost, the simplicity of the hardware will make moving optical technologies from one bus to another relatively easy, potentially mitigating the long-range cost issue.
- Less chance of sensor interference with other systems both on and off the bus.

Disadvantages of optical technologies

- Typically increased sensitivity to environmental factors such as lighting, weather or pavement conditions. This is particularly true with passive vision-based guidance systems.
- Potentially higher per vehicle cost as the sensors involved (be they cameras, lasers or radar) are likely to be more expensive than some of the other technologies.
- If the pavement markings used by the optical system are not consistent with normal roadway markings, they are likely to cause confusion for the drivers of other vehicles that would share lanes with the guided buses.
- Temperature sensitivity – Typical off-the-shelf consumer/commercial cameras may not operate at the high temperatures outside a bus operating in an area such as Florida

during the summer months. This may require use of industrial/military cameras, and/or environmental management strategies which could add to the size and cost of system.

Even in light of advances in image processing software and the computer hardware on which it runs, the applicability of vision-based systems is limited to relatively structured environments for which good atmospheric conditions exist. This is evidenced by the Las Vegas CiViS system. For its operation, the CiViS needs a specific pattern to recognize, and it needs a clear view of that pattern. Frequent roadway maintenance may be needed to maintain sufficient visibility of the optical pattern, which has been a significant problem with dust, dirt and melting roadway asphalt in Las Vegas. Areas in which snow, heavy rain, and fog are endemic cannot reliably be serviced by a vision-based system. As these conditions are faced by a significant number of U.S. transit agencies, vision systems should be ruled out as a primary electronic guidance mechanism for these transit agencies.

Figure 1.2 Las Vegas CiViS bus with vision based guidance

It is also important to note that repainting of lines is not an inexpensive proposition; in fact, Las Vegas intended to use the CiViS guidance system only for precision docking, and not for lane assist. This decision was based on the fact that painted stripes last only for a short period of time when exposed to the high heat and intense UV rays of the desert. It would have been too expensive to periodically repaint the lane markers over the entirety of the bus route.

1.2.2.2 Magnetic Guidance

Magnetic guidance systems use magnetic material (e.g., magnetic tape or discrete plugs) located on, adjacent to, or embedded in the roadway. Sensors of the magnetic field onboard the vehicle are used to determine the vehicle's position relative to the lane and to provide lane keeping assistance to the driver.

Advantages of magnetic technologies

- Insensitive to environmental factors such as lighting, weather and pavement conditions.
- Very high position accuracy possible.
- Static coding of other information is possible – for example: warning of upcoming road curvature by varying the polarity of discrete magnets in a known pattern.

Disadvantages of magnetic technologies

- Sensitivity to other ferromagnetic material in the vicinity of the bus such as components in the vehicle, roadway structural supports or reinforcing rebar may distort the magnetic field. Such changes in the background magnetic field are sometimes hard to isolate and can deteriorate system performance.
- The low field strength provided by the in-road magnets limits the maximum range for which the lateral position can be reliably estimated.
- Requires some modifications to the infrastructure. This will not be a substantial impediment when there are only a limited number of lane-miles where lane-keeping assistance is required.

The California PATH Program has performed extensive experimentation and development of magnetic marker based lateral control/guidance system on different vehicles. In one such example, a supplemental guidance display was installed in a California Department of Transportation (Caltrans) snowplow in order to improve the safety and efficiency of snow removal operations. Lane position information was calculated based on the magnetic markers embedded in the roadway and “read” by a single magnetometer array comprised of seven magnetic sensors installed at the front of the snowplow. Signal processing of the magnetometers provides lateral position measurement relative to the center of the lane, longitudinal position relative to mileposts, and yaw angle estimate. Binary coding of the magnetic markers when installed (north pole up vs. south pole up) also can provide information about upcoming roadway characteristics, e.g. the direction and radius of the curves (Tan et al., 2001; Zhang et al.,).

During the period of October 6 to December 1, 2000, a magnetic guidance equipped Buick LeSabre underwent a series of tests on the test track of the Public Works Research Institute (PWRI) in Tsukuba City, Japan. The installed system provided information to either an automatic steering command to the steering actuator, or a display providing a preview of the future vehicle position (predictor) if the driver does not correct his steering action. The design of this guidance display was optimized to make it very easy for the driver to steer the vehicle accurately, even in zero-visibility conditions. Furthermore, PATH also demonstrated a smooth switching method that was previously developed, allowing the driver to change between automatic and manual steering control at any location or time that he commands (Tan and Bougler, 2001).

Recently, two 40 foot CNG New Flyer buses and one 60 foot articulated New Flyer bus were retrofitted with magnetic maker based lateral control system. Precision inline and s-curve docking and stopping maneuvers of the 40 foot bus were successfully demonstrated in Washington DC and San Diego with 2 cm accuracy laterally and 10 cm accuracy longitudinally. Lane assist, lane change and automated/manual transitions were demonstrated on the I-15 HOV lanes in San Diego, achieving 15 cm lateral tracking accuracy at up to 65 mph for both the 40 foot single unit bus and 60 ft articulated bus.

Toyota is developing an Intelligent Multimode Transit System (IMTS) which uses magnetic markers as the lateral sensing system. Experimental studies on a test course show ±5 cm lateral deviation at up to 30 km/h (Aoki and Suyama, 2000). In 2005, Toyota demonstrated their IMTS system at the Aichi World Exposition near Nagoya, Japan, with platooning, lane assist and precision docking functions, and carried more than 10 million passengers on the IMTS buses..

The Phileas bus has an electronic lane assistance and precision docking system with all-wheel steering. The system is based on magnetic markers every 4 meters in the road surface and works at speeds up to 80 km/h and under most weather conditions. When driving in automatic mode, the Phileas bus requires only 6.4 m of width for two-way dedicated lanes at 70 km/h (http://www.apts-phileas.com).

1.2.2.3 Wire Guidance

Wire guidance systems share many similarities with magnetic guidance systems, but in this case, an electrified wire is buried in the pavement and its position relative to the vehicle is sensed. While it shares the same advantages and disadvantages as magnetic guidance, it has an additional disadvantage. The electric current required for this type of system to operate will be lost if the wire is broken, causing a single point of failure rendering the system inoperable. This could be a particular problem in northern climates where deflections in the pavement due to temperature variations may cause wire breakage. This introduces a liability into the system which is beyond the control of the operating agency.

1.2.2.4 Global Positioning System (GPS) Guidance

GPS guidance systems use the constellation of satellites maintained by the U.S. government and special receivers to localize the vehicle on a digital map of the environment. This information can be used to determine the vehicle's position relative to the lane.

Advantages of GPS technologies include:

- Little infrastructure modifications are required. To achieve the kind of accuracy required for electronic guidance, a GPS system may require the installation of a base station for differential corrections, but the cost of such a base station is relatively low.
- Relatively high positional accuracy is possible.

- Because of their flexibility and independence from the local infrastructure, GPS technologies can provide benefits beyond the specific narrow lanes where control assistance for the driver is required. This would be particularly useful in BRT scenarios where the buses need to leave the narrow, designated travel lanes and travel on normal roads. This extended functionality could include lane assist similar to that available on the narrow lanes or passive warnings/advisories directed at the driver.
- Dual use – In addition to their use in lane assistance, GPS technologies can be employed to support other functions that may be important for a BRT system including precision docking, longitudinal (headway) control, vehicle routing, scheduling, etc.
- Systems are relatively immune to dynamic environmental influences. GPS systems are not degraded by weather, lighting or pavement conditions.

Disadvantages of GPS technologies include:

- Relatively high per vehicle cost. GPS sensors accurate enough to provide useful lane position data are relatively expensive compared with the other technologies.
- Sensitive to static environmental factors such as occlusion of sky by trees, bridges, overhead signs, nearby buildings, hills etc., resulting in significantly degraded performance and require additional expensive sensors (e.g. inertial sensors) to fill in the “gaps”.
- For differential GPS in which the bus receives GPS-correction radio signals transmitted from a private service provider, excellent positioning accuracy can be achieved; however the service provider controls the differential broadcasts, which introduces a potential single point of failure beyond the transit agency’s control.
- GPS signals, being very weak, are vulnerable to interference and “jamming”, which can create concerns about their reliability and availability for such a safety-critical application.

California PATH has conducted several projects dealing with improvement of GPS technology and vehicle control/guidance with GPS based positioning system. Carrier phase signal processing and DGPS/INS (inertial navigation system) integration were investigated to see if they could overcome problems associated with GPS based positioning systems such as accuracy, latency and low updating rate. Researchers found that the integrated CP (Carrier-Phase) DGPS/INS system could provide vehicle position, velocity, acceleration, heading and angular rate at 150 Hz with accuracies (standard deviation) of 1.5 cm, 0.8 cm/s, 2.2 cm/s/s, 0.1 deg and 0.1 deg/s respectively (Farrell and Barth, 2002). A CP DGPS/INS based control system was tested onboard a PATH vehicle at the Crow’s Landing test facility. Decimeter accuracy was achieved up to 70 mph under open sky conditions (Farrell et al., 2003; Tan et al., 2003).

In Minnesota, research was conducted in which CP DGPS was used for snowplow guidance. Integration with INS was used to address the GPS signal loss due to certain intermittent blockage from bridges and canyons. If the signal loss lasted less than 30 seconds, estimation from INS was used for guidance. For signal losses greater than 30 seconds, magnetic tape embedded in the roadway was used to provide lateral position (Minnesota DOT, 2001; Minnesota DOT, 2002).

In the Minneapolis/St. Paul Metro Area, a lane support system retrofitted on a Metro Transit bus was demonstrated to be capable of steering a 9.5 ft wide bus along a 10 ft wide “bus only shoulder.” Two CP DGPS receivers (Trimble ms 750) were used to provide centimeter accurate position, roll and heading information. Thirteen cm (standard deviation) lateral tracking error was achieved at speeds up to 35 mph (Donath et al., 2003).

Most GPS based control/guidance research is carried out in an ideal or a semi-ideal environment where sufficient satellites are available with little problem of blockage and multi-path error. In reality, such an environment does not always exist. Urban canyons, nearby buildings, bridges, overpasses, tunnels, roadside trees, even a heavy vehicle in the next lane will occur with high statistical certainty. The always-changing satellite configuration makes the reliable prediction of such degraded characteristics virtually impossible in many cases. Accuracy may deteriorate or be lost for significant periods of time.

1.2.3 Comparison of different technologies

The Metro team summarized the infrastructure and vehicle characteristics of different electronic guidance technologies using two tables (Donath et al., 2003). Based on the findings from the European study visit and PATH’s experience with guidance technologies, this table has been updated. Note that when reviewing different technologies for use in specific BRT applications, in addition to the characteristics listed in the table, the following additional key points also need to be considered:

- Technology and infrastructure need to be compatible with the types of weather and road conditions that may be encountered, including bright sun, fog, snow, ice, heavy rainfall, strong wind, high humidity, and extreme temperatures. External hardware will be required to withstand dust and water as well as sand and salt.

- A system failure should not prevent the bus from operating under driver control within the BRT infrastructure (although this may be at reduced speeds) or off route.

- No single point of failure should be able to jeopardize the availability or the operation of the system. This is especially important with aspects beyond the control of the operating agency, such as GPS differential correction beacons.

TABLE 1.1 - Summary of Infrastructure Characteristics for Various Lane Assist and Precision Guidance Systems

Technology	Production Status	Road Infrastructure Cost/Mile	Supporting Infrastructure Costs	Dedicated lane	Weather Limitations	Topographical Limitations
Curb Guidance	Presently out of production	$2.65M / mile	0	Yes	Heavy snow & ice problematic	None
Rail Guidance	Prototype (2 systems)	$15.5 M / mile	0	No	Ice may jam up guide rail	None
Vision Guidance	In Production	None	Cost of surveying, painting and repainting reference stripes	No	Yes – fog, heavy rain, snow in air, or on ground, UV & heat on paint stripes	Some – roads must be kept clear so stripes are visible.
Discrete Magnets	PATH Prototype	None	$10,000 mile (survey & installation of magnets)	No	No	None
3M Magnetic Tape	No Longer Supported	None	$3 - $5 per linear foot of magnetic tape, installed	No	No	None
DGPS	University of Minnesota Prototype (one system on one bus)	None	$250 / lane-mile to map roadway, GPS base stations at $25 K each + base station software ~$100,000	No	No	Yes – need clear view to sky for satellite signals

Source: Bus Rapid Transit Lane Assist Technology Systems, Volume 1 **[with a few modifications]**

TABLE 1.2 - Summary of Vehicle Characteristics for Various Lane Assist and Precision Guidance Systems

Technology	Vehicle sensor cost	Computational Complexity	Lane Assist/Precision Docking	Control Features	Bus Features
Curb Guidance	\$15,000 - \$30,000	None	Yes/Yes	Mechanically actuated steering system	Conventional bus equipped with mechanism
Rail Guidance	Not Known	Low	Yes/Yes	Mechanical or Hydraulic connection to guide rail	Low floors, Euro design, 3 articulated sections
Vision Guidance (CiViS)	Vehicle cost is ~\$1 M per vehicle, estimate 10% is technology cost	High	Yes / Yes	Electrically actuated steering system	CiViS – Low floors, Euro styling
Discrete Magnets (PATH)	\$5000-\$10,000 for sensors,	Medium	Yes/Yes	Electrically actuated steering system, retrofit	Retrofit onto existing bus
3M Magnetic Tape	\$5000-\$10,000 for sensors,	Medium	Yes/Yes (modifications needed for low speeds)	Electric steering, retrofit	Retrofit onto existing bus
DGPS (University of Minnesota)	\$25,000 - \$30,000 for sensors (in volume)	Medium	Yes/Yes	Electric steering, retrofit	Retrofit onto existing bus

Source: Bus Rapid Transit Lane Assist Technology Systems, Volume 1

1.3 Human Factors Considerations

Electronic guidance systems for transit lane assist and precision docking applications are intended to enhance the performance of transit buses, thereby to improve service quality. On the other hand, these technologies must be designed to be easily adopted by bus drivers and will reduce, rather than increase, their stress level and improve the safety. Previous research has shown that urban bus driving is a stressful occupation that can lead to long-term health difficulties. While there have not been any long-term studies of an implementation of lane assistance systems, initial short trial studies have had some promising results, suggesting that such a system may aid a decrease in the stressful nature of urban bus driving. There is however a clear need for future research to investigate how driving with an electronic guidance system affects subsequent driving when driving in a manual mode, as well as issues such as how well humans can perform as the monitor of such a system and how well drivers, once trained, can take control if a fault does occur.

1.3.1 Bus Operation is a Stressful Vocation

It has been suggested that urban bus operation is a very stressful vocation (Evans et al 1999). In a review of a number of previous studies, Evans (1999) concludes that bus operators have higher rates of the conditions listed in Table 1.3 compared with people from similar occupations:

Table 1.3 Bus Operator Health Problems (Evans (1999)

Condition	Urban bus operators compared with people from similar occupations
Cardiovascular disease	Increased levels
Gastrointestinal disease	Increased levels
Driver absenteeism rates from illness typically related to stress related causes	Increased levels
Raised blood pressure	Increased levels
Neuroendocrine stress hormones	Have elevated levels

Given the high levels of stress related illness much research has been conducted to determine why urban bus driving is stressful. Meijman et al (1998) suggest that bus operators have three main psychosocial demands in their job; maintaining schedule, giving good customer service and operating the bus safely. As can be imagined the above demands often compete, which can cause stress for a bus operator. In addition to these three main stressors, Evans et al (1999) lists from the literature the following physical stressors evident in the bus operator's task: dealing with traffic congestion, and ergonomic factors related to bus operation such as noise, and climatic conditions (thermal and air quality).

In order to gain a better understanding of the urban bus driver's task, Gobel et al, 1998 performed an eye-movement analysis of German bus operators. The total breakdown of visual scanning patterns can be seen in Table 1.4 below:

Table 1.4 Temporal distribution of gaze directions (from Gobel et al 1998).

Gaze direction	Percentage
Outside	73.2
Mirrors	10.8
Window jambs	8.4
Instruments	3.2
Customer service objects	5.0

One of the concerns about adding electronic guidance is that monitoring it should not take the driver's time away from monitoring the forward view. To date there has been no study that we are aware of that has compared drivers' visual practice with and without electronic guidance. This issue however does provide us with a design specification that an electronic guidance system should not require any more attention than other instruments.

1.3.2 Previous efforts to make urban bus operation less stressful

In a study by Grosbrink et al (1998) ways to decrease the physical stressors encountered in bus operation were investigated. Though a review of ergonomic solutions to physical stressors is out of the scope of this document, interested readers should review Grosbrink et al (1998).

Evans et al (1999) sought ways in which to decrease the stressful nature of urban bus driving. The researchers implemented changes in Stockholm, Sweden and compared feedback from drivers operating on "improved routes" with drivers operating on similar routes with no "improvements". The "improvements" included; construction of a separate bus lane for the most congested sections of the routes, changes in the routes to minimize difficult turns and bottlenecks, the construction of "passenger peninsulas" where possible to bring the passengers out to the bus to avoid pull-overs to the curb, the installation of bus traffic signal priority system and installation of an electronic bus information system for passengers. As all the implementations were done at one time, it is not possible to determine the effect of each change individually; however, the researchers report that based on driver questionnaires, observations, and psycho-physiological measures the changes did reduce occupational stress among drivers. Interestingly, many of these interventions are somewhat similar to many of the changes proposed in current BRT plans. More specifically, lane assist will remove the need for drivers to pull over to the curb and should also minimize difficult turns.

1.3.3 Previous Lane Assist Human Factors Research

Ward et al, 2003 conducted research to determine the impact of using a lane assist system developed to provide a "vehicle control coping support function" when operating a bus on narrow dedicated highway shoulders. The researchers had bus operators drive under the following three conditions: in a lane adjacent to the narrow shoulder lane manually, on the shoulder lane manually, and on the shoulder lane with the lane assist system on. The results from this study suggest that while their experimental system did not reduce subjective measures of stress for drivers it did improve the stability and control of the vehicle. The authors concluded that the reason that the subjective stress levels did not decrease could be attributed to the perceived unreliability of their system and the need for drivers to interpret what the feedback that the system was giving them meant.

In order to test how bus operators' workload is affected by an automated docking system Collett et al (2003) measured electrodermal activity (as a measure of workload) both with and without an automated docking system during 5 different docking scenarios. The promising results from this study suggest that while drivers' workload with a new system did initially go up, it was reduced as the drivers became more experienced with the system. The authors of this study also simulated failures of the system that they had not trained drivers for, which not surprisingly resulted in increased measures of workload. It would have been interesting to see what effect a failure would have had on workload measures if the bus operator had been trained for the event. The researchers in this study found that docking with the system was about 5 cm more accurate both at the front and in the middle of the bus, closer than when the drivers performed the same docking manually. Survey responses from the drivers also suggested that the system was useful and easy to monitor, facilitated docking and thus decreased operator workload. In their summary Collett et al (2003) stressed that for technologies to improve the safety of bus operation, operators must learn how these technologies work.

To further emphasize the importance of operators fully understanding how technologies work and when to intervene, Sheridan (2002) [p. 30] cites the example of a fatal Washington DC Metro accident which was attributed to an unclear management policy regarding when a driver could take over in case of automation failure:

> "The system had been set in automatic control by the operations control center, even though some operators had requested a manual control mode because of icy track. However, one new operator, when he found his train was not slowing as expected, was intimidated by what he perceived to be orders not to countermand the automated braking system. His train overran the Shady Grove Station by 470 feet (about 143 m) and struck another train at full speed."

As electronic guidance technology is still being developed, it is unclear what the long-term effect of such systems will be. Previous research into automated highway systems suggests some questions that are also applicable to the application of electronic guidance of urban buses. Of those questions put forward by Levitan (1998) we suggest the following two are relevant to electronic guidance:

a) What effects will automated travel have on manual driving?
b) What role can the driver be expected to play when a failure occurs?

1.3.4 Driver Vehicle Interface (DVI) Design Issues

Electronic guidance systems should be designed to be as easy to use as cruise control in a car. It is expected that the guidance function will be engaged with simple actions and that the driver will be given clear confirmation regarding the engagement/disengagement of electronic guidance and system status.

The driver will interact with the electronic guidance system through a Driver-Vehicle Interface (DVI), which will provide the necessary information and the means to make an informed decision regarding transition to or from electronic guidance at any given time. The DVI may include a visual display (which could be a simple array of LED's, an LCD screen, or a Heads Up Display), auditory communication, tactile feedback (such as a vibrating seat), and haptic feedback (such as brake pulsing), as well as a set of simple controls. The design of the system should promote good mode awareness, which means that individual switches and displays should not have different meanings at different times such that they could cause driver confusion. Furthermore, the design of the system should assist the driver in recognizing, diagnosing, and recovering from errors. It is important to note that the DVI should be designed to support the goal of reducing driver workload in challenging driving conditions

Most, if not all, deployments of electronic guidance, will involve route sections where the infrastructure support for guidance is available and sections where it is not. For this reason, a smooth transition from manual to assisted driving and back is essential. The transfer of control could potentially be achieved in two ways. The first is driver initiated, requiring some action from the driver to engage or disengage the auto steering mode. The second method is a system-initiated transfer to/from auto mode. Even when the transition from auto mode to manual is automatic, say at the end of a narrow tunnel, the driver must take some sort of action to let the system know that he is back in control. If the driver does not take the required action to switch back to manual steering, the vehicle may come to a complete stop. An example of a driver initiated auto-steering handover would be as follows:

a) As the bus approaches narrow sections of roadway the system indicates to the driver that they are in an auto-steering enabled area.
b) The driver decides to transition to auto steering and acts to engage the auto-steering mode.
c) While in auto steering mode the driver controls speed and monitors the forward and side views.
d) Prior to the end of the narrow roadway section, the system indicates to the driver that the bus is approaching the end of the auto-steering enabled area.
e) The driver takes action and transitions to normal steering. If the driver does not take the required action to switch back to manual steering the vehicle comes to a complete stop.

In case of an emergency, the driver will have the ability to exit or override the system in a number of quick and simple ways such as pushing down on a button, applying a large torque to the steering wheel, or applying hard braking. Redundancy and system fault detectors need to be built into the system so that if a system fault occurs, the system can switch to a back-up method of control and indicate to the driver that the system requires maintenance.

A number of human factors recommendations for automated systems come from research on automated highway system (AHS). The guidelines below are taken from FHWA-RD-97-125. We have taken only the guidelines that we feel would apply to transit bus electronic guidance implementations.

- If the driver must accurately position the vehicle to be able to transition, then a guideline should be painted on the roadway or an in-vehicle display should graphically depict the vehicle position relative to a reference point.
- Establish mechanical restrictions to guard against control transfer until the driver is prepared to initiate it.
- Provide attention-getting displays (e.g., rumble strips) for areas where an automated-enabled segment of roadway ends.
- If the driver disregards an alarm the vehicle should come to a controlled stop.

It is important to acknowledge that implementing electronic guidance to urban bus driving will change both the driving task and the operational environment. Such changes in any system can have both positive and negative impacts. It is therefore important to clearly define what the system is prior to implementation and to determine what the expected changes might be so that any potential negative impacts can be designed out.

Urban bus operation can be thought of as a system comprised of five main entities: the bus, other traffic and operating conditions, the operator, the passengers, and the transit agency. Each of these entities has the ability to influence all the other entities. For purposes of this section we have looked specifically at the bus operator’s task, though it is important to recognize that the other entities have the ability to impact the operator’s task.

1.4 Terminology Definitions

Electronic guidance and lane assist have been interchangeably used by different people for different applications. In this report, “electronic guidance” refers to technologies that provide automated steering or driver assist functions enabling a vehicle to follow a certain predetermined trajectory under automatic control. The term “lane assist” refers to the application of electronic guidance technologies to allow a transit bus to maintain a transit vehicle in a designated lane or a desired trajectory while “precision docking” refers to application of electronic guidance technologies to deliver accurate, reliable and repeatable maneuvers that allow safe, convenient, and expedient boarding and alighting operations at bus stations constructed in a train-platform manner. Electronic guidance can be combined with longitudinal control. It is noted that for certain applications, it is advantageous to integrate both the lateral and longitudinal functions for performance requirements. For instance, precision docking that demands accurate positioning of vehicles laterally and longitudinally may be difficult to accomplish with drivers controlling the stopping maneuvers.

1.5 Report Organization

This report addresses the needs that can be served by lane assist systems and the requirements that these systems will need to meet in order to be found beneficial. It is intended to be complementary to the report that was previously produced by the University of Minnesota for FTA and Metro Transit (Donath, et.al., 2003), adding further information about safety issues and incorporating the findings from close interactions with stakeholders at key transit properties who could become early adopters of lane assist systems.

Chapter 2 reports on the findings of the case studies that were performed with AC Transit, LACMTA, the Lane Transit District and San Diego Transit to identify their needs and requirements for lane assist systems.

Section 3 provides a benefit and cost analyses showing the needs of the transit lane assist and precision docking systems and an economic analysis of a subset of the economic benefits that can be gained from lane assist systems (dwell time savings at bus stops for precision docking and reductions in busway width for automatic steering). Deployment issues are also discussed in this chapter.

Chapter 4 provides a preliminary description of performance requirements and technical specifications for transit lane assist and precision docking systems.

Chapter 5 is the summary.

Additional information is provided in Appendices as follows:

Appendix A: Effects of Tight Turning Radii on Needed Lane Width

Appendix B: Questions for Lane Assist Requirements Workshop

2.0 CASE STUDIES

In order to study the needs and define the requirement specifications for transit lane assist and precision docking systems, the project team studied the potential application of lane assist technologies for, and conducted a series of workshops at, four partner transit properties, including:

- Workshop with Lane Transit District (LTD) in Eugene, OR on July 29, 2003
- Workshop with San Diego Transit and San Diego Association of Governments (SANDAG) in San Diego, CA on September 10, 2003
- Alameda-Contra Costa Transit District (AC Transit) Workshop at PATH facility in Richmond, CA on February 12, 2004
- Workshop with Lane Transit District (LTD) drivers in Eugene, OR on March 31, 2004
- Workshop with Los Angeles County Metropolitan Transportation Authority (LACMTA) in Los Angeles on September 3, 2004
- Combined Workshop at University of California Richmond Field Station on July 29, 2004

The purposes of these workshops were to acquire first hand information from transit operators and drivers, to derive a common set of needs, benefits and costs, and to translate these needs and desires into system requirements and specifications.

The case studies and workshops differed considerably across these transit properties because of the different maturity of development of the BRT concepts within these properties. Specifically, Lane Transit has already progressed further in its own development of its BRT system and in its consideration of lane assist technologies than the others, so this case study had significantly more depth than the others. In contrast, AC Transit is in the midst of planning for its new BRT service but has only begun consideration of the opportunities provided by lane assist. LACMTA already has a number of BRT lines in operation and is considering whether lane assist and precision docking technologies can be beneficial to improve the operation. San Diego Transit, on the other hand, is just starting to think about where it could apply BRT service, so it had not begun considering lane assist possibilities prior to the project workshop.

The formats of the workshops with the four transit properties were similar, beginning with an overview presentation of lane assist and precision docking systems and following with discussions of various issues related to the needs, requirements and deployment of these technologies. The discussions were led by PATH researchers. An exception was the AC Transit workshop, which also provided participants with the opportunity to drive an automated bus developed by PATH. One additional workshop was organized by LTD to focus on obtaining inputs from drivers.

As the culmination of the project, representatives of the participating transit properties came together in a one-day workshop at the University of California Richmond Field

Station on July 29, 2004, followed by a teleconference on August 3, 2004, to address issues that could not be covered within the workshop schedule. These were opportunities to provide comments on the draft project report, with particular emphasis on the definition of requirements for lane assist systems. More importantly, this was the opportunity to gain cross-fertilization of ideas from transit properties that have approached lane assist systems from somewhat different perspectives, and to see whether a common set of requirements could address all their needs. The workshop was attended by representatives of AC Transit, Lane Transit District and San Diego Transit, and they were joined on the teleconference by a representative of LACMTA. Those who attended the workshop had the opportunity to drive a test bus equipped with precision docking capability, so they could experience it in action from the driver's perspective.

The inputs obtained from the representatives of the four transit agencies through six workshops were organized into key issues including applications, benefits and costs, design considerations, requirements, and deployment issues for lane assist and precision docking systems.

2.1 Potential Applications

Among the four partner transit agencies, Lane Transit and AC Transit have already considered how to incorporate lane assist and precision docking systems in the designs of their current BRT systems. The project team therefore conducted more detailed case studies on the LTD and AC Transit BRT corridors, while potential applications of lane assist and precision docking systems for LACMTA and SANDAG were discussed in their workshops.

2.1.1 LTD Case Study Example

As a result of a major investment study conducted between 1992 and 1999, Lane Transit District (LTD), which serves the towns of Eugene and Springfield, Oregon, is in the process of implementing a Bus Rapid Transit (BRT) system. It is based on light-rail transit operating principles, but uses buses in service that is integrated with key components of the existing automobile transportation infrastructure, such as roads, rights-of-way, intersections, and traffic signals. This system is more affordable and flexible than light rail and allows for incremental construction and implementation which can be easily tailored to meet the specific transportation needs and opportunities within individual neighborhoods and transportation corridors. BRT offers many advantages compared to regular bus service for LTD, including service frequency, increased capacity, and speed.

One of the key features of the BRT system, reduced dwell times at stops, will be achieved primarily by use of off-board fare collection. It is hoped that precision docking can be added in the future. By creating a bus platform at the same height as the floor of the bus and eliminating a gap between the platform and the bus, all passengers can board easily and quickly.

If LTD’s BRT system is to achieve its service goals, some form of electronic guidance system will be needed to allow it to operate in narrow right-of-ways and to precision dock. Although the BRT buses have been ordered, no guidance system has been chosen.

Proposed station spacing is approximately every half-mile, resulting in ten stations, eight of which will be new facilities. Stations will be similar to light rail stations, with a high level of passenger amenities, including benches, shelters, ticket machines and passenger information.

BRT in Eugene and Springfield will be developed incrementally in order to adjust to community needs and as resources become available. The pilot corridor will be the route from the Eugene Station at Willamette Street and West 11th Avenue in Eugene, to Franklin Boulevard, past the University of Oregon, and along South A Street in Springfield to the new Springfield Station. This corridor will introduce the service to the community, offering bus riders and motorists first-hand experience with its benefits. Future routes that will connect to the pilot corridor are currently under consideration for both Eugene and Springfield.

Consistent with the approved design, there will be exclusive transit lanes from the Eugene Station to Walnut Street. From Walnut Street to McVay Highway, the BRT system will travel in mixed traffic. Glenwood is expected to redevelop over the next 10-20 years, and it was felt that until the redevelopment occurs, it does not make sense to spend limited funds on roadways that are likely to change. However, once across the bridge into Springfield, BRT will travel in exclusive transit lanes between the bridge and the new Springfield Station at Pioneer Parkway East and South "A" Street.

Eight BRT stops between the Eugene Station and the Springfield Station are constructed. All traffic signals along the route will be designed to give priority to the BRT vehicles. The second Eugene BRT corridor will be Coburg Road, originating at the Eugene station and running over the Ferry Street Bridge on Coburg Road to Crescent Avenue. Alternative street routing will be examined as part of the design process. Connections to the Pioneer Parkway corridor, being developed in Springfield, will also be pursued.

The City of Springfield and LTD have selected the Pioneer Parkway corridor to be the next BRT corridor developed in Springfield. The Gateway area has seen extensive employment growth and increases in traffic congestion. More frequent and reliable transit service is necessary to serve this growing area. The City of Springfield is planning an extension of Pioneer Parkway, north of Harlow Road, to serve the new Sacred Heart Hospital and Riverbend development area.

Figure 2.1 LTD Proposed BRT Corridors

LTD has identified the New Flyer BRT vehicle as having the desired vehicle attributes, such as alternative power, clean, quiet, low-floor, tram-like in appearance, for service in the Eugene/Springfield area. The ability of a vehicle with lane assist capability to maintain a predefined path throughout the corridor would result in less right of way needs, increased operational efficiency, and easier passenger access/egress.

LTD believes that vehicle guidance is the next major development in transit. Specifically, vehicle guidance will solve the following specific problem areas:

- Limited Right of Way: The vehicle is able to follow a pre-programmed route; thereby minimizing lane width requirements and increasing operating speeds while reducing the amount of right of way needed.
- Dwell times: The guidance system will allow the vehicle to stop very close to a passenger platform. When combined with a passenger platform that is raised to the height of the floor of the vehicle, boarding by all passengers, including people in wheelchairs, is accomplished easily and quickly and without the need for special lifts or ramps.

- Image: The guidance system will allow the vehicle to operate in a similar manner to a rail- guided vehicle. This image, combined with the other BRT features, will attract a new market of riders who have traditionally been reluctant to use conventional bus service.

- Maintenance costs: Smooth acceleration and deceleration will enhance passenger comfort and also emulate rail operations. Over-braking and acceleration of vehicles will be reduced, thereby decreasing vehicle maintenance.

(Inputs from LTD workshop, July 29, 2003):

LTD foresees deploying electronic guidance at stations, stops, intersections, and along Franklin Boulevard, which may require contra-flow (narrower) lanes. On this route, high speeds are not required (need only 30-35 mph). If the system handles both steering and speed control, it would achieve its most efficient operation, but then it may be difficult to keep the driver engaged in the driving process. Operation involving electronic guidance will be primarily on the median side of traffic in exclusive rights-of-way and, where possible, segregated.

2.1.2 AC Transit Case Study Example

AC Transit (the District) operates over 100 local and Transbay bus routes. Six of these routes carry over 15,000 daily riders. The District's Bus Rapid Transit project is planned for their heaviest route, which today carries 30,000 daily riders. The BRT corridor would serve three downtowns (Oakland, Berkeley and San Leandro); three regional medical facilities (Alta Bates, Summit Medical Center and San Leandro Hospital); the 30,000 student University of California, Berkeley campus, Vista Community College and the Bayfair Mall. The residential density in the corridor varies between 11,000 and 23,000 persons per square mile. The corridor serves 1/3 of the residents and half the jobs in Oakland. The project currently has $100 million in local and regional funds.

The entire 18-mile corridor would use existing arterial streets and would convert two 12-foot traffic lanes into dedicated bus lanes. Much of the route is 75 feet wide (curb to curb). In some cases, the alignment is also the most direct route for bicyclists and is designated as a future Class II bikeway in the Oakland Bicycle Master Plan. The conflicting demand for road space has motivated the District to seriously consider lane assist solutions that could permit narrower bus lanes.

AC Transit would like to explore opportunities to implement the magnetic guidance technology along AC Transit's BRT corridor. AC Transit sees that lane assist technology can provide the following benefits:

- Accommodation of bike lanes for the entire route
- Accommodation of additional traffic lanes at congested locations
- Reduced infrastructure cost (approximately 12% of busway costs)

- Increased safety
- Preservation of on-street parking in local commercial districts
- Reduced dwell times and enhanced ease of boarding and alighting at BRT stations. Since the new buses will load wheelchairs at the center door, positioning the bus becomes both more important and more difficult. Precision docking could be critical here.

In addition, AC Transit views longitudinal control as a potentially important component of its Bus Rapid Transit program and key adjunct to the lane assist technology. Longitudinal control will enable smooth accelerating and braking that will arguably permit buses to operate with the comfort and safety of rail. From the passenger's perspective, longitudinal control would minimize the harsh movement of the bus and reduce on-board passenger falls. Longitudinal control would also reduce wear and tear on the bus's drive train and brakes, reducing maintenance costs and fuel consumption.

(Inputs from AC Transit workshop, February 12, 2004):

AC Transit sees that lane assist and precision docking systems can enhance its new BRT corridor along Telegraph/International/E. 14th St. These technologies may also be implemented along the existing San Pablo RAPID BRT line**.**

The subject of which technology would be best was brought up and discussed briefly. Most of the discussion dealt with magnet systems, which seemed the most flexible for the applications envisioned. One person thought that a vision system, with its highly visible painted line, would be better in that people could see easily see the busway. It was pointed out that the same effect could be achieved with magnets by simply painting a line connecting them. Another possibility would be to use a different type of pavement or to paint the entire busway surface a different color.

2.1.3 SANDAG's Considerations in Lane Assist and Precision Docking Systems

(Inputs from Sandag workshop, September 10, 2003):

The evaluation of lane assist systems is most closely linked and can be appropriately considered in conjunction with the "Transit First Showcase" project that is administered under SANDAG. Particular features of the targeted showcase project are in line with the characteristics of transit electronic guidance systems, including:

(1) Exclusive right-of-way to bypass congested areas, and use of shared lanes where streets are operating smoothly. The portion of the route that is designed for exclusive transit lanes is El Cajon Blvd. from Park Blvd. to 43rd Street.
(2) Stations will have uniform design features, with accessibility to passengers with disability, in compliance with the Americans with Disabilities Act.

(3) Offering ride quality of rail and operating qualities of buses, and ultimately increasing ridership considerably.

Lane assist systems could enhance the service of transit buses and become an integral part of the developments for the following aspects:

- Train-like ride quality
- Service quality and reliability
- Transit station design and ADA compliance
- Construction cost savings in exclusive transit lanes.

At the time of this workshop, San Diego area stakeholders had not yet focused enough attention on the lane assist technologies to be able to offer specific feedback regarding their needs, priorities or concerns related to lane assist, limiting the value of the current case study.

2.1.4 LACMTA's Considerations in Lane Assist and Precision Docking Systems

(Inputs from LACMTA workshop, September 3, 2004):

During the discussions several areas within the MTA's current route system were discussed as potential locations where a lane assist and/or docking system could be used:

- A strip of 13 miles on Wilshire Boulevard. This is the corridor where most of the bus accidents happen (due to the higher number of miles driven in this corridor). A recent effort using the Sheriffs department to increase traffic enforcement saw a drop from 11% of all accidents to 9% of all accidents. Typically the Rapid buses have 30% fewer accidents than local buses (on a per mile driven basis)
- The Orange Line, which is 14 miles long, 13 miles of which are on an exclusive lane constructed in former rail right-of-way. The other mile is on an arterial in mixed traffic using transit signal priority to expedite travel time. There are 22 new NABI articulated buses providing the service on this corridor. There are 13 stations (with the eastern most station being the North Hollywood MetroRail Red Line station). There is a parallel bike path, as well as new parking facilities at five of the stations, but costs associated with these items should be the same with or without lane guidance. Stations are approximately one mile apart and buses will have 5-10 minute headways during the peak periods. Since the curb on this line will be at the same height as the bus floor this could be used as a demonstration project for precision docking.
- San Fernando Valley demonstration line – there is a section going under the I-405 freeway where there are tight tolerances between columns, so precision docking could be useful.
- Line 710 has a new concrete roadway. There was discussion about the height of the footpaths here, with no consensus, but it seemed that the difference between the curb and the floor height of the Nabi articulated buses' front door was not that large.

There was consensus that the time needed to deploy wheelchair ramps was not great and that level boarding was not necessarily going to be a huge advantage or need.

- Sections where narrow lanes already exist. Three sections of the Wilshire Metro Rapid Corridor, including a segment of roadway in Santa Monica where tree-lined medians have recently been constructed, in Beverly Hills, and east of the "Miracle Mile" between La Brea and Western Avenues in Los Angeles, already have lanes as narrow as 10-10.5 feet wide.

2.2 Benefits and Costs

2.2.1 Benefits

(Inputs from LTD workshop July 29, 2003):

In the LTD service area there are quite a few people with disabilities. Precision docking would allow much faster boarding. Additionally, in an informal poll, 15 of 17 attendees at one of the workshops preferred electronic guidance to mechanical lifts for wheelchair access, with frequent lift maintenance cited as one of the principal reasons.

If BRT and electronic guidance are able to reduce travel times, increase reliability, and eliminate the second-class stigma of bus travel, ridership should increase significantly, thereby reducing congestion, pollution, and commute times, and increasing farebox returns. Lane assist and precision docking also have the potential to reduce collisions as well as passenger injuries.

Workshop participants discussed the fact that, since subsidized public transit is the norm, what sort of return on investment should be required in order to justify the expense of electronic guidance? The participants felt that while forecasting can provide at least an estimate of increased revenues due to increased ridership as well as savings from increased reliability and safety, there is no easy way to quantify such intangibles as quality of life gains from reduced congestion and commute times, a cleaner environment, and reduced stress.

Workshop participants felt that LTD must get "reasonable payback" in about 10 years, with initial costs (which it was believed would be paid, for the most part, with federal funds) and ongoing operating costs as the most important to consider. It was further hoped that LTD could break even on traditional operational costs, including those involving infrastructure, with delay reductions and increased reliability providing a portion of the cost reductions. Another potential source of operating cost reduction would be increases in the lifecycle of other bus systems. Brakes, for example, may last longer under electronic guidance.

(Inputs from AC Transit workshop, February 12, 2004):

A commonly discussed benefit in this and other workshops is increased trip time reliability and the saving of time. These could be achieved by reducing dwell times through faster boarding of wheelchairs and other riders with mobility problems, queue jumping, and signal priority. Time saved through faster boarding could be significant, since census information along the corridor (in an area around the length of the corridor with a width equal to the distance people are normally willing to walk to bus stops) shows that the percentage of disabled persons is twice the average of the Bay Area as a whole. An ancillary benefit to faster boarding is that it would help resolve a stressful issue for drivers who must deal with passengers whose patience is often strained by the time it takes to load and secure wheelchair passengers.

Funding is always a problem for public transit agencies and AC Transit is no exception. To sell the system, benefits would have to be significant. Bundling electronic guidance with other systems such as collision warning and speed control would be seen as a much more attractive package.

While time and reliability benefits are important in attracting new riders, for transit agencies an important question when considering new technology is not simply how to decrease dwell times at individual stops but whether the total time saved will allow them to decrease the number of buses needed to service the route. This is where the real cost savings would come into play.

Passenger falls when the bus stops are a problem for AC Transit. The busy (trunk) lines have a high probability of standees, which makes the problem worse. Any technology that could provide smooth, predictable acceleration and deceleration would have the potential to reduce the number of claims against the agency, which could produce significant cost savings. Certainly, precision docking would help in this area since station stops would be consistent and predictable. Additionally, a smoother, “rail-like” ride might make it possible to do away with the requirement to secure wheelchair passengers. However this would require that guidance be used on the entire route, something which is not feasible in the foreseeable future.

Two additional potential benefits were also mentioned. The first was the possibility that precision docking would lower some of the ADA mandated door-to-door paratransit service costs by allowing delivery of passengers to fixed-route buses rather than door-to-door. Second, guidance might allow lane width to be decreased from 12 to 10 feet, leaving more space for other purposes such as parking or bicycle lanes. It may be difficult to monetize this when calculating benefits, though.

The ultimate measure of success of a transit system is whether or not people are using it. The measure of success for a transit system change is therefore its effect on ridership. This can be difficult to measure, since it is often impossible to isolate the specific effect of the change in question. The implementation of vanpools, for example, was accompanied by fare adjustments, service changes, and balky fareboxes. On a positive note in relation to BRT, a before-and-after study is being conducted on the San Pablo RAPID corridor and, thus far, it appears that there has been a 12 % increase in ridership since the start of the new BRT service there.

(LTD driver workshop, March 31, 2004):

Drivers generally are in favor of lane assist and precision docking systems and believe that these systems offer the following benefits:

- Enables fast at-grade boarding (reducing dwell time)
    - Access for riders made easy and more efficient
    - Enhances boarding for wheelchair passengers
- Enables buses to operate within narrow lanes that facilitate dedicated BRT deployment without increasing operator stress
- BRT deployment may lead to an increase in ridership, if riders experience faster transit times.

Two drivers commented that they felt it was the "way of the future," one driver said he "did not want to see a BRT application implemented without it", and the drivers also felt that if the system worked properly it could reduce their stress level. The drivers felt that the most beneficial aspect of the system for their application would be the docking.

(Inputs from combined workshop, July 29, 2004):

There was general consensus that the benefits of Lane Assist need to be stated very clearly. Most important to LACMTA are safety, reliability, and consistency. Reducing dwell time is not at all a selling point for them. They cautioned that the theoretical dwell time savings can get watered down considerably when it is filtered through the entire staffing and rostering process. It is important that all steps in the operations process be accounted for so that a more realistic assessment of benefits can be made.

Safety and liability were major topics of discussion. One of the risk management participants strongly disagreed that the introduction of a lane assist system would see a large reduction in their accident costs, which were estimated at $40 million in 2003. Of this amount, approximately half was the result of severe injuries to pedestrians who were hit by a bus as it made a right turn. These type of accidents cost somewhere in the range of $1.5 to 4.5 million each.

While pedestrian accidents would not be helped by lane guidance, this still leaves $20 million worth that could be. Paradoxically, it was felt by participants that there could be an increase in liability for prior accidents when safety improvements are added (it is seen as your company acknowledging that there was a hazard that should have been addressed sooner). This actually occurred when the agency introduced a 4-quadrant gate at several intersections. It was noted, however, that LACMTA would not reject a new technology system simply because of the possibility of liability for prior accidents.

Bus versus a stationary object is by far the most frequent crash type, although these crashes usually have low direct costs as they occur in crowded streets at low speeds. However there are many hidden or indirect costs (administrative, loss of bus in service, involvement of 3 to 4 transit operations supervisors, union involvement) for these accidents which contribute significantly to the actual total. Thus the little, every day stuff of 5-6 accidents/day (a few thousand annually) quickly add up.

Because there exists the potential for a lane guidance system malfunction to cause a crash, one of the risk management participants noted that in order for the LACMTA to do a demonstration line they would require that the manufacturer or the funding agency have $50 million of insurance to cover the risk. At present when MTA purchases any equipment for a bus, it has to come with $20 million of insurance. The extra $30 million would be required for the perceived extra risk of the new technology. This issue could overwhelm a startup company trying to get into this business. We will need case law on this and should closely monitor the Las Vegas BRT.

The biggest economic benefit a large transit property would see from time saving associated with exclusive busway operations or precision docking would be if it became large enough to eliminate a bus from a major route without diminishing quality of service (estimated at $250 K per year for 16 hours of daily operation by AC Transit). However, this was of less value to Lane Transit because their services need to operate in multiples of 60 minutes to maintain a regular schedule and they could not save a bus.

It is important to have a way to factor the time savings from precision docking into the transit agency estimates of hourly operating costs so that it can be compared to other alternatives. The AC Transit General Manager is excited about potential time savings from docking, but needs a better way of quantifying that. LACMTA has recently deployed a 14-mile BRT facility to standards comparable to an LRT line, with full-scale stations, in the San Fernando Valley. It could be considered as a test site to compare dwell times with and without precision docking.

2.2.2 Costs

(Inputs from LTD workshop July 29, 2003):

It is anticipated that there will be $1.6 M that won’t be spent on vehicles. At this time, it is not known how the decision will be made regarding spending the money on electronic guidance. A final question considered was whether or not it would make sense to equip the entire fleet with guidance.

(Inputs from combined workshop, July 29, 2004):

The participants felt there was a need to work with transit planners to determine cost savings. It was emphasized that the only way for time savings brought about by new technology to pay off is if the savings are large enough to allow a bus to be taken out of service while maintaining the same level of service.

First, the following costs, as they relate to any new technology, must be estimated:

- Capital
- Operating

- Maintenance
- Installation
- Training
- Upgradeability/lifecycle

Then do a calculation for, as an example, 100 buses on five miles of Wilshire Boulevard. What would the saving be for one year, two years, and beyond (it would be expected to lose money for the first few years)? What's it going to save over the life of the system (it would need to last more than 10 years)? How many miles would you need to implement to be able to take a bus out of the system?

It was stressed that what is really needed is to have more capacity for the same operating costs, which would need to involve scheduling system experts in the analysis. Since ridership is largely transit dependent for buses (and rail), lane assist technology, by itself, may or may not attract more people since it will be invisible to most people. What is needed is to increase ridership without increasing costs. Putting more people on an already crowded system could actually cost money since another bus would eventually need to be put into revenue service.

Costs were also recognized to be in a different category from system requirements, but there are clearly going to be trade-offs that determine what costs will be acceptable or unacceptable for deploying lane assist systems. The transit properties will need to be able to judge the costs of the systems against the benefits (financial and other) that they will gain from use of the systems. The discussion gravitated more toward the benefit side than the cost side.

Cost estimates need to be done carefully to separate the cost increments that are specifically associated with use of the lane assist system. For example, in the case of precision docking at stops or stations, the entire cost of the stop or station should not be associated with the docking function, but only the cost elements that are different because of precision docking.

2.3 Requirements

2.3.1 Performance

(Inputs from LTD workshop July 29, 2003):

With specific applications in mind, what kind of performance can LTD expect to realize from electronic guidance? Additionally, should these expectations be judged by current bus or light rail standards?

As a starting point, the system should be easy to operate within the full range of applications. Next, ride comfort, which is best defined as smoothness of operation, is very important especially since LTD anticipates fewer available seats and more standees (some with bikes) on board than on standard buses. This being the case, smooth acceleration, deceleration, and lane tracking are critical. At a minimum, performance under electronic guidance during these phases should be better than in the manual mode.

Tracking accuracy is important under two application scenarios: operations in narrow lanes and precision docking. Since Franklin is an Oregon state route, ODOT is very interested in the BRT lane width along this route and the ability of the guidance system to stay within it. Several workshop participants wanted to know if an S curve or a series of curves would require a greater lane width, not only to compensate for rear wheel tracking but also electronic guidance sloppiness.

For docking, ADA requires a distance no greater than two inches horizontally and 5/8 inch vertically between the bus entrance and the station platform. This presents a special problem for articulated buses since without a long straight approach, the rear of the bus would not be in alignment with the front. This would necessitate a specific platform shape, with the aft part angling out so as to align with the rear bus section.

(Inputs from AC Transit workshop, February 12, 2004):

For a number of reasons, some more perceived than real, people like rail better than buses. One reason is that trains provide a smooth ride, with few, if any, unexpected movements. To be more “rail-like,” workshop participants felt that the system should be smooth enough that it would “not spill my drink.” Passengers should not have to contend with any unexpected movement. The smoothest ride would be provided by a system that had longitudinal as well as lateral guidance. The demonstration ride at the beginning of the workshop seemed to fit this need.

The following categories of performance attributes were offered for consideration:

2.3.1.1 Lane-tracking accuracy

(Inputs from LACMTA workshop, September 3, 2004):

Opinion was split about how important it was to have minimal lateral deviation (less than 5 cm) at high speeds. It was agreed that a high accuracy system should be available, as it is critical on the arterial routes.

(Inputs from combined workshop, July 29, 2004):

Increased lane-tracking accuracy makes it possible to operate the bus in a narrower lane. Both Lane Transit and AC Transit thought that the narrower the feasible lane width, the better in general, but they could not choose a specific target lane width value without knowing the relative costs and technical feasibility of achieving that level of lane keeping performance. For example, as the lanes get narrower it becomes less feasible for the driver to take over operation in the event of a system fault, so the consequences of faults and the reliability requirements become more severe with narrower lanes. Although the driver could be expected to drive the bus in a 10.5 foot wide lane, this would not generally be possible in a 9.5 foot wide lane. It is also essential that head-on collisions between guided buses (or even mirror-hitting collisions) be virtually impossible, because otherwise the system would be unacceptable to the public. This means that the steering accuracy requirements would have to be tighter for a bidirectional busway without a physical separation between directions than for a busway with a median or a single-lane bidirectional busway.

Lane assist on a busway can produce significant economic benefits if it can reduce lane width. Lane Transit reported right of way costs in excess of $20 per square foot, and noted a specific instance of having to pay $80 K to acquire a single parking space in front of a restaurant. They can provide information about construction costs per square foot of busway surface based on the bids they have received for construction of their busway.

Lane tracking accuracy should not be defined as a fixed required value, but should depend on speed to define a kinematic envelope of space needed by the bus, according to Lane Transit. Urban street applications could have tighter constraints than freeway applications, according to AC Transit. LACMTA is currently more concerned about being able to operate at a higher speed, with safety and confidence, in the fixed-width lanes that they have available for their use (perhaps increasing from 25 to 35 mph), rather than in reducing lane width. These different priorities for lane assist would lead to different technical requirements.

AC Transit suggested that if the technical capabilities were defined up front, then transit properties would be able to design projects to take advantage of those capabilities. A PATH researcher suggested that a “window” of tolerable performance could be defined first, and then desirable performance goals could be specified for higher accuracy if needed for specific applications.

2.3.1.2 Precision Docking Accuracy

(*Inputs from combined workshop, July 29, 2004):*

The starting point for discussing docking accuracy was the ADA requirement of no more than 3 inch lateral gap and height differences within +/- 5/8” between the bus floor and the loading platform.

Meeting ADA requirements without ramps would be a “high end” docking requirement, but then there is a heavy responsibility to maintain the roadway geometry accurately and the costs of building loading platforms that are sufficiently level with the bus floor at all bus stations would be high, according to AC Transit and LACMTA.

If the purpose is meeting ADA requirements and ramps have to be provided anyway, precise tolerances are not needed. It would be very desirable to eliminate the lifts and ramps entirely in order to gain a real cost saving, but this seems hard to achieve in practice because of the abnormal cases in which the bus would be prevented from reaching its docking station. The transit agencies still felt the need for a ramp or lift as a backup system in those cases.

AC Transit noted that their bus fleet is evolving toward low-floor buses with ramps rather than high-floor buses with lifts. When the buses are used at stops that don't have high-level boarding platforms they would still need to be equipped with ramps, so that cost cannot be eliminated in general. However, if they are only used rarely the maintenance costs should be reduced and time would still be saved at the stops with boarding platforms. With AC Transit's newer buses having the ramp at the middle door rather than the front door, the major time saving would be in avoiding repeated re-positioning of the bus to get that door lined up well enough to deploy the ramp.

Reducing dwell times at stops should be the main docking benefit for LACMTA. This could even be as subtle as passengers not needing to hesitate to look down before stepping out of the bus, as AC Transit observed they do on buses, but not on trains with level platforms. Everyone recognized the lack of solid data on the potential time saving that could be gained from precision docking, and this was identified as a primary goal of a field operational test, to compare dwell times at stops before and after precision docking is put into service.

AC Transit observed that safety benefits could be gained from "consistent" rather than "precision" docking, by not hitting roadside objects while entering and leaving the bus stop. This would have less demanding performance requirements than precision docking.

Precision docking can best be "sold" initially to transit boards and managers based on passenger convenience, ease of general boarding, ease of wheelchair handling, and the impacts these might have on increasing ridership, rather than on direct time savings. It is too difficult to determine the quantitative savings that precision docking would produce in wheelchair boarding times, but transit boards could decide that it is still "the right thing to do" without knowing the exact time saved, based on considerations such as reducing the stigma associated with disabled passengers delaying a bus full of other passengers.

2.3.1.3 Lane tracking ride quality

(Inputs from combined workshop, July 29, 2004):

Ride quality cannot be made worse than it is today with a driver, and should be at least as good as a current LRT or bus. Better ride quality than today would be a plus. The participants thought this would be more associated with pavement roughness and vertical movements of the bus than with the lateral movements.

2.3.2 Safety

(Inputs from LTD workshop, July 29, 2003):

While hand-over of control and driver alertness/involvement generated the most discussion during all three workgroup sessions, there was little in the way of consensus or conclusions. Key to this problem was the lack of personal experience with or availability of data on electronic guidance system operations. One point of agreement was that although the DVI is likely to be agency dependent it should be technology independent.

Handover can occur under two circumstances, normal and emergency. Under normal conditions, how can it be established that the driver is willing and able to take over control from the computer? First, of course, the driver must be alerted to the pending hand-over, then some positive action must be taken by the driver. If the driver fails to respond and the bus cannot continue under computer control, the bus must be brought to a stop.

There are a number of ways to alert the driver, including visual, auditory, and haptic (e.g., seat vibration or feedback in the steering wheel or brake) cues. In the case of auditory cues, care must be taken so as not to upset passengers or present an opportunity to fake an accident for a false alarm. Could such a warning be made low enough in volume so that passengers could not hear it, yet loud enough to get the driver’s attention?

Once it has been established that the driver is prepared to take over, will further action be required or will the indication of readiness be the takeover itself, such as pushing a button, turning the wheel, or tapping the brake?

In the case of an emergency or system failure, some action would be required on the part of the driver, possibly the same type of action used to establish control during a normal hand-over. It would be possible to have a panic button so that speed and braking disengage but there would have to be some positive indication that the driver’s hands are on the wheel before automatic steering disengages. Another possibility would be to have the driver tap the brake pedal to disengage the brakes and turn the steering wheel with sufficient torque to take over steering. Drivers would need to keep their hands sufficiently close to the steering wheel in order to be ready to take control.

In the event of a failure, many preferred having the bus come to a complete stop while steering straight ahead (but what happens if failure occurs on curve?), at which point the driver would take control. The ideal situation would be to receive some advance warning (using system redundancy to maintain control). Some worried about coming to a stop in mixed traffic or an intersection.

Driver involvement or how to keep the driver in the loop presented the most difficult problem. With a highly reliable system, drivers will depend on the system more and more over time, with the possible result that they will be easily distracted by other routine chores. This could lead to a diminished ability of the driver to respond to emergencies. This would be especially true in long, computer controlled sections where both steering and speed control were automatic.

The key question, then, is how to keep the driver engaged and vigilant and ready to take over manual control without having some obnoxious signal alarm bells going off? Among the suggestions was to have the driver control the speed at all times, although it was felt that in narrow bus lanes drivers would have a tendency to drive slower than the optimal rate. Also, automatic speed control would improve reliability. Another idea was to require positive driver control through all intersections.

(Inputs from combined workshop, July 29, 2004):

It was well recognized that safety benefits are difficult to estimate, but the transit properties would prefer to see estimates of the percentages of safety incidents that could be saved through use of lane assist technology. In the absence of authoritative data about these percentages, it would still be useful to see examples estimated assuming hypothetical percentages such as “what if 50% were saved”? Consider different crash types and how lane assist would affect each. Qualitative arguments may be sufficient at this early stage in development of the technology, since quantitative data do not yet exist.

Risk management groups in the transit agencies will need to understand all system failure modes and consequences of those failures in order to develop a sufficient comfort level with a new, potentially safety-impacting, technology such as lane assist. Lane Transit would go to their insurance company to address risk management issues (they are self insured up to $1 million, but have insurance above that).

Perception of safety by the drivers, insurance industry and public will be important, and can be aided by statistics such as the LA Metro Rapid example of 30% lower crash rates than local buses in the Wilshire corridor.

2.3.3 Reliability and Robustness

(Inputs from LTD workshop July 29, 2003):

There will be four vehicles at any given time in peak service with one spare. LTD cannot afford to have two vehicles go down simultaneously. A service interruption, even if it’s just an easy replacement or switch, could cause problems since the BRT corridor is one of the most heavily traveled and carries the most passengers.

(Inputs from AC Transit workshop, February 12, 2004):

The ability to withstand relatively rough treatment is very important. Buses will be subjected to rough city and county roads that could shake loose circuit boards and connections. Additionally, equipment that is attached to the underside of the bus could be damaged or displaced enough by road debris and deep potholes to affect performance.

Finally, the external equipment must be able to withstand the high-pressure hoses during maintenance washing.

(Inputs from combined workshop, July 29, 2004):

The discussion on reliability and robustness issues quickly gravitated toward the more complicated and challenging safety issues, so that they were heavily enmeshed with each other.

Lane assistance cannot be allowed to fail in a way that would produce a crash, because that would preclude it from being used again and would have serious ramifications for the transit agency's future applications of advanced technologies. There was no consensus on a tolerable frequency of faults of lesser severity, and eventually it may be necessary to provide specific examples of choices in order to elicit the trade-offs between system costs and fault frequency.

Two-way operation on a busway is particularly sensitive, in the opinion of AC Transit, so if a bus suffers a failure the buses approaching in the opposite direction should also be notified to prepare their drivers to take evasive action in order to minimize the possibility of a head-on crash.

Standards or regulations from DOT or AASHTO would be desirable in order to provide national consistency and perhaps some liability shielding. Certification procedures are needed, and the state Public Utilities Commission (PUC) would probably be interested in this issue because of their involvement with rail transit systems already. Their processes tend to be time consuming, but would be valuable if they produced consistent and reasonable criteria.

Systems need to be suitable for use in all weather conditions encountered throughout the country, yet buses are also specified differently in different regions (for example, differences in air conditioning capacity depending on climate). The transit property representatives thought that it would be useful to have a table showing the limitations of each of the main technology classes (optical, magnetic, GPS, mechanical) relative to weather and other environmental conditions (such as urban canyons), so that properties could easily determine which technologies could be suitable for use under the conditions that they face.

Redundant systems, using more than one of the technology classes in combination with each other, can provide some protection against vulnerability to the weaknesses of a single technology. However, this increases the cost by requiring more equipment to be installed and maintained.

2.3.4 Availability

(Inputs from LTD workshop July 29, 2003):

As currently envisioned, LTD can live with an electronic guidance failure as long as the buses are still operable in manual mode, although system performance would obviously be degraded. If a segregated lane is being used when a guidance failure occurs, there should be some means for the bus to move into a normal traffic lane and continue to operate.

Cost is an important issue when considering availability and reliability. If 90% availability could be achieved for $1 million while 99% was possible for $2 million, what should the choice be? Infrastructure availability must be close to, if not equal to, 100%.

(Inputs from combined workshop, July 29, 2004):

Availability requirements appear to be closely related to the ability of the driver to take over for a faulted system. If the lanes have been narrowed greatly (to 9 feet) to take advantage of lane assist, the driver would not be able to maintain lane tracking, so the consequences of a fault would be greater because the faulty bus would have to be pulled out of service. On the other hand, with a 10.5 foot lane, a driver should still be able to drive the bus, though perhaps at a lower speed or with a higher degree of concentration than would normally be needed. In the latter case, the availability of the system would not need to be as high.

None of the properties were considering such a large fleet of lane assist buses that differences in system availability would affect the number of buses needed (the size of the spare bus fleet needed to ensure uninterrupted service).

2.3.5 Maintenance

(Inputs from LTD workshop July 29, 2003):

Perhaps the most important point made during the maintenance discussions was that incorporating electronic guidance should not materially change current maintenance procedures. Guidance systems, therefore, should have service intervals at least as long as other systems so that they can be checked at routine maintenance intervals, currently every 12,000 miles or approximately 40 days. Additionally, the life cycle of the system should be at least equal to the bus lifetime (15 to 20 years) with maintenance included.

The system itself should be “plug and play”, with “black boxes” that could be repaired in-house, sent out for repair or, depending on component cost, simply discarded. LTD wants a simple diagnostic system, one that is short and easy to understand. It should have self diagnostic capability at the system, sub-system, and component level. LTD would also like the system available for integrated diagnostic checks with other bus systems.

As with any other bus system, a decision must be made as to how involved agency staff should be in repair work as opposed to outsourcing. With only five guidance equipped buses, does it make sense to make repairs in-house? How steep is the learning curve for such systems? The general feeling was that outsourcing does not work very well for a small agency such as LTD. If the maintenance work were to be kept in-house, would a new, dedicated repair bay be required? Might it be possible to combine with other agencies to form some sort of regional transportation facility?

While the various electronic system components can be shielded from everyday roadway wear-and-tear, the sensors are vulnerable to roadway hazards and conditions. Daily sensor calibration will therefore be necessary. It was suggested that this should be done each day as the bus left the yard, perhaps by running it through a short calibration course.

Infrastructure maintenance was also discussed. Even though the street is owned by the city or state, special bus ROWs would probably have to be maintained by the transit agency. This being the case, infrastructure maintenance requirements should be kept to a minimum. Certainly, using concrete rather than asphalt for dedicated and segregated busways will help. The question arose as to whether magnets would work with some snow (yes).

(Inputs from AC Transit Workshop, February 12, 2004):

Since the results of requirements discussions from the Lane Transit District workshop were incorporated into the AC Transit presentation, participants in this workshop focused on those areas that were either unique or especially important to them. Chief among these was maintenance.

Since even the toughest equipment can be adversely affected by road conditions, there is a need for some form of daily calibration. As long as the location sensing equipment is within certain limits, this calibration would allow the system to compensate for position input error until the bus was brought in for its routine maintenance.

At the present time, AC does not outsource any maintenance work. The consensus seemed to be that they would like to maintain this practice, although they would send individual parts back to the supplier, as is currently the case with fueling and communication systems.

(Inputs from SANDAG workshop, September 10, 2003):

The high precision of the lane assist and precision docking system will increase the wear of the pavement along the tire tracks. There is a need for installation of more durable pavement along the busway, which will increase the cost of the deployment. If the guided buses are operated on the existing roadway, it is a concern to the transit agency that the transit agency may have to take over the maintenance of the bus track pavement (which is typically maintained by locals) or the condition of the pavement may deteriorate more quickly than that used by regular buses. A suggestion was made to study the impacts on the pavement and special cost-effective guidance-compatible pavement designs.

(Inputs from LACMTA workshop, September 3, 2004):

All the systems require the roads to be maintained very well – at present there is a big problem with this as it would add significantly more cost to a system, making the system more comparable in price to rail. It was thought that the current road surface would present the following issues:

- Pot holes (streets are not well maintained) – roads are currently grade "c" or "d" on average and in some places they are "e".
- Each docking station would need to be re-engineered (adding cost)
- If each system-equipped bus follows the same tire tracks, better pavement would be needed – more like airports
- The system would have to adapt to different road crowns in different sections.

(Inputs from combined workshop, July 29, 2004):

The vehicle's lane-assist system should include a self-diagnostic procedure for use each morning in the yard before starting the first bus run of the day. Periodic preventive maintenance intervals should be consistent with those for other major bus subsystems. For any infrastructure elements needing special maintenance attention, the transit operator would need to pay the other agency with lead responsibility for road maintenance along the route, but this could be subject to complications of interpretation between agencies (What is the normal maintenance, and what is the additional maintenance specifically attributable to the bus system?).

Bus stops would need to be built and maintained to tight tolerances for precision docking. For example, Rouen, France had difficulty maintaining the vertical tolerances for their precision docking system. Variations from one bus to another also need to be considered when they are operating with the same fixed infrastructure elements.

2.3.6 Compatibility with Existing Infrastructure and Vehicle

(Inputs from LTD workshop, July 29, 2003):

While a segregated busway would probably not present problems, with dedicated lanes, care must be taken to avoid using roadway markings that might confuse other drivers. It was brought up that the bus lanes would be made of concrete (i.e., a different color) to contrast with the normal traffic lane's asphalt surface. One point that has not been discussed with ODOT is what happens at intersection where concrete and asphalt would cross.

(Inputs from AC Transit workshop, February 12, 2004):

There was a recommendation that the added in-vehicle equipment for the lane assist system needs to be able to communicate with other electronic systems on the vehicle using the standard data bus. Also, when the question of reduced tire wear from precision docking was raised, AC Transit noted that this would not be a significant benefit for them because their tires were leased rather than owned.

2.4 Design Issues

2.4.1 Vehicle Technologies

(Inputs from LAMTA workshop, September 3, 2004):

Mechanical Guidance: One of the participants had ridden on one of the systems and thought that it was “a little jerky” just as the system was coming on, but not at all jerky once the system was moving.

CiViS – Vision Based System: LACMTA has reviewed the specification of the CiViS vision based system and determined that it does not meet the minimum speed for their Metro application. However, participants were interested in learning about experience obtained in the Las Vegas application.

Magnetic Guidance: Participants were interested to know the speed of docking and how much time it took to hand over control and to get it back.

(LTD driver workshop, March 31, 2004):

All of the drivers requested that the route/system be designed so that it could be driven manually. This issue was driven in part by bad experiences with new technology that has “worked one day then not the next for no good reason”. The drivers mentioned that this distrust of technology is an issue for both the drivers and for their passengers. One of the driver/ trainers had practiced docking on both sides of the bus and did not find it difficult. The general feeling among those present was that with a small amount of practice all the drivers should be able to manually dock the bus to the tolerance expected by the proposed Lane County implementation. The Lane County implementation is planning on having bridge plates come out from the bus onto the platform, which will somewhat reduce the need to get really close to the platform.

Door Open Assistance from System: One issue bought up by the BRT project engineer was the need to have automated door assistance so that the doors on the side of the bus that the platform is on are the only ones that open each time (it will be recalled that in this planned implementation some stops will be on the right and some will be on the left). Lane Transit District is pursuing a technology solution to this issue.

Situational Awareness: Situational Awareness refers to the ability to identify, process, and comprehend critical elements of information around you. The questions with regards to this issue came out of both human factors automation research and the previous general Lane County lane assist workshop. In the prior workshop a suggestion had been made that the system should provide the drivers with information that a busy section such as an intersection is coming up and to be alert. The drivers did not want this idea implemented, since they felt that they would not loose situational awareness, and this type of “reminder” would quickly get annoying. One driver commented that as trained professional drivers they cannot stop scanning the environment – and they do this even when someone else is driving.

2.4.2 Infrastructure Design

(Inputs from LAMTA workshop, September 3, 2004):

The importance of bus stop design was stressed. MTA has found that with their new rapid stops customers board faster because the barrier arms appear to “force” patrons into a line at the bus stop, which facilitates much faster boarding. For this reason it was felt that the longitudinal bus stop position was very important (some thought more important than the horizontal position as it was thought that using the new ramps was not time consuming.)

One of the issues that the drivers were most concerned about was that the design of the docking station takes into consideration the likely flow of pedestrians. The drivers mentioned this because they felt that passengers getting off the bus and rushing to catch it present one of the most dangerous hazards in operating a bus.

(LTD driver workshop, March 31, 2004):

One area where we wanted feedback was the issue of merging with traffic from the left and the right (this was a potential issue because the Oregon implementation is to have bus stops on both sides of the street). Interestingly, the drivers did not feel that the merging would be an issue, but they felt that if their mirrors were set up correctly they could merge with traffic equally well from either side.

The drivers did, however, feel that depending on the station design they may need assistance to merge back into the traffic (independent of which side they were merging from). There was a general consensus that the ideal situation for a merge is if they can get the bus up to the surrounding traffic speed before they have to merge, which one driver compared to “a freeway onramp”. Other suggestions to make merges safer were: to have a signal prior to the merge so that the bus enters traffic on a green light, have signs warning traffic that buses will be merging up ahead (though there was some discussion about how successful this would be as previous implementations of signs have not worked well), and implementing a stop sign prior to the merge area.

(Inputs from combined workshop, July 29, 2004):

The infrastructure issues would arise mainly for dedicated bus lane facilities rather than mixed flow (where the infrastructure would not generally be tailored for bus use).

Having a distinctive appearance in a dedicated bus lane (such as a different color of pavement) helps to deter other drivers from straying into that lane and interfering with the bus operations. On the other hand, guidance systems that depend on a distinctive pavement appearance (such as the CiViS optical guidance system with its unique pattern of pavement striping) are probably not usable in a mixed-flow lane because of the likelihood of confusing other drivers.

It was generally agreed that dedicated bus lanes with precise steering would need concrete rather than asphalt pavement in order to avoid rutting of the pavement because of concentrated tire loading in the identical tracks. Heavier passenger loading of Metro Rapid buses at LACMTA is already producing instances of accelerated pavement wear on routes and at stops.

Bus stops are already being paved with concrete "bus pads" at AC Transit and LACMTA, and this was generally seen to be important to maintain accuracy for precision docking, in addition to avoiding excessive wear of the pavement.

BRT street design standards are needed to facilitate approval of construction, especially on state highways, not just for lane assist systems, but for other infrastructure design issues that would not be consistent with conventional road construction. This should be part of the charter of the new California BRT Task Force, chaired by the Caltrans Division of Mass Transit.

2.4.3 Driver Vehicle Interface (DVI)

(LTD driver workshop, March 31, 2004):

Hand-Over of Control: There must be a manual decision to leave the station, because this way the driver gets to make adjustments for standing passengers and can start off at different speeds. Drivers report that they will leave a stop faster if all the passengers are seated as opposed to some standing or if there are passengers with mobility deficits making their way to seats. The drivers felt that once they were up to speed they would then hand control over.

The drivers were in general agreement that a DVI should conform to the following rules:

- Needs to not take attention away from driving (forward view)
- DVI interaction should be no more complicated than other on-board systems
- DVI must not contradict any already existing known relationships or trained/learned behaviors
- System should keep driver in the loop
- DVI should provide feedback to the driver about what state it is in as well as cue the driver when they need to take an action
- Controls shall be separated spatially and be of different colors and shapes
- Must be easy to use and require short glances
- Should not increase driver's stress levels
- DVI should provide the driver with the following 3 pieces of information

    - What is the current state of the system (binary answer, manual on or electronic guidance on)?
    - Can the driver initiate a change at this time (binary answer: driver can request transfer of control to guidance system or driver cannot request transfer of control)?
    - Is the electronic guidance system working properly (binary answer: either system is fine or system has a fault)?

(Inputs from AC Transit workshop, February 12, 2004):

On a bus, passengers' sensibilities have to be taken into account when designing the DVI, so audio and visual cues and warnings would have to be more discreet in order not to unduly alarm riders. Another issue is the possible need to integrate guidance systems with other electronic systems already installed on the bus, using a common data bus.

2.5 Deployment Issues

2.5.1 Institutional Issues

(Inputs from LTD workshop, July 29, 2003):

Political battles in Oregon are different for light rail and bus. There is no political/public support in this area for bus right of way – the prevailing view is one of "I have the right of way in my car now and don't want to give it up." The emphasis is more on personal movement rather than what is good for society as a whole. With this being the case, it was felt that educating the public about the benefits of BRT would be necessary to get the public to buy into the new system.

Two additional topics were broached regarding deployment of an electronic guidance system: necessary changes in traffic laws and driver assignment. The introduction of electronic guidance may necessitate changing current laws not only to enforce bus-only, dedicated BRT lanes, but also to allow certain BRT operations (e.g., it is against the law in Oregon to have hands off the steering wheel). These changes may require action at the local, county, and even state level. Since the Oregon legislature meets only once every two years, change may be slow and/or difficult.

(Inputs from AC Transit workshop, February 12, 2004):

Enforcement is another big deployment issue. How will non-bus traffic be kept out of dedicated bus lanes in the absence of physical barriers? Even now, bus drivers often can't get all the way into the bus stop because something is blocking the space. It is also often difficult to pull out of a stop and re-enter traffic, especially with a longer bus whose rear-end tends to fishtail. Finally, what can be done about traffic compliance from delivery trucks that could obstruct the roadway?

One of the major deployment issues to affect AC Transit's proposed BRT route is its effect on parking. Merchants are very sensitive to anything that might negatively impact their business and are often unwilling to accept change of any sort. In Berkeley, for example, there is neighborhood resistance to the BRT project among some merchants along Telegraph Ave., which is somewhat difficult to understand in that only a small percentage of their business is generated by people who drive on Telegraph itself. Perhaps it's not an access issue at all, but merely fear of the unknown. Part of the problem may also be that, in conducting an EIR, the worst-case scenario or condition must be included. While these are usually moderated during the design phase, the worst case is often what people remember.

(Inputs from LACMTA workshop, September 3, 2004):

MTA mentioned two policy decisions that need to be considered when studying the use of guidance technology along the Wilshire Corridor:

1. L.A. Department of Transportation Policy: If a lane narrower than the standard 12-foot lane is dedicated to bus-only use, then this lane must use some form of lane guidance technology. Further explanation of this policy is needed.
2. City or County of Los Angeles Policy: Consistency with Livability Guidelines relative to arterial roadway expansion is mandatory, thus prohibiting creation of a 12-foot wide lane along current 10-10.5 foot wide segments of Wilshire since the necessary modifications to the "street furniture" (traffic lights, light posts, drainage culverts, trees, etc.) in order to expand the right-of-way would violate the Livability Guidelines.

2.5.2 Risk Management

(Inputs from LTD workshop July 29, 2003):

While subjectively there may be different implications if an accident is caused by the driver or by an onboard computer system, from a practical standpoint there would be no difference. The transit agency employs the driver and owns the system/subsystem that failed. Failure of electronic guidance would be the same as a tire blow out or brake failure – it is just another piece of the equipment. To date, there is no precedent at LTD as to whether negligence could be claimed in the event of an equipment failure caused crash, since it has never previously occurred.

In the event of a failure, the question arises as to who would be ultimately responsible: the transit agency, the bus manufacturer, or the guidance system manufacturer. While the transit agency would be the first party sued, will they be able, in turn, to be compensated by the bus or system manufacturers? Given the potential liability issues, it was felt that bus manufacturers would not be willing to retrofit their buses with an electronic guidance system.

The final topic regarding risk management was the availability of "black box" data from the new electronic guidance system that might be useful to crash investigators. LTD is currently getting some data off the bus such as speed and camera view. On request, this data is turned over to the police per a reciprocal agreement.

2.5.3 Driver Acceptance

(Inputs from LTD workshop July 29, 2003):

With regard to driver assignment, it was generally felt that there should be a core group of BRT qualified drivers (some extra training would be involved) while still maintaining the current bidding process. While seniority will determine who gets to drive, the system should be such that all drivers will be able to operate it. If a driver is interested in becoming qualified they must become “certified” to operate the system. Drivers who are not interested should be able to opt out and not drive these buses. One potential problem is that it could be argued that if there is a need for specialized driver training, then those drivers should get paid more.

(Inputs from LACMTA workshop, September 3, 2004):

Questions were raised about the amount of training that would be required and how easy the system would be to use. Comments were made that there may be a push for more money from the union as this has happened when they have previously introduced new technology.

(LTD driver workshop, March 31, 2004):

The drivers felt that the initial training needs to come from manufacturers, so that all questions can be answered and so that they can gain a full understanding of how the system works. The drivers agreed that the training should give drivers an accurate mental model of how the system works, and conditions where they should take over. When asked about ways in which their response to failures could be practiced, one driver commented that it should be similar to having a tire blow-out in that a trainer would not blow-out one of the tires but they would tell a driver what they might see, feel and experience and what they should do.

(Inputs from combined workshop, September 3, 2004):

After having driven a prototype lane assist system, the workshop participants felt that it would not be difficult for the drivers to learn to use the system under normal driving conditions. Driver acceptance and training issues were dominated by consideration of the need to practice handling worst-case fault scenarios. This could involve use of a training simulator but also “fire drill”-like practice out on the road to ensure that drivers are comfortable and proficient with taking over control in the event of a failure.

2.5.4 Public and Passenger Acceptance

(LTD driver workshop, March 31, 2004):

The drivers said that the reduced dwell times might conflict with passenger service/passenger expectations in the following two ways:

The drivers suggested that when driving their usual route they will wait for regular passengers if they are rushing to catch the bus. The drivers felt that this was part of their job to maintain good customer service and that it was expected of them both from the passenger running to catch the bus as well as from the passengers already on the bus. Two of the drivers suggested that one solution to this could be a passenger education campaign. The BRT project engineer also suggested that this may be less of a problem if passengers know that another bus will follow within a certain short period of time. The drivers felt that this might be something that passengers would get used to over time. A related solution was to have an off-board announcement that the doors are about to close and that the next bus will arrive in x minutes.

There was a general consensus that while passengers with reduced mobility capability (those in wheelchairs, on crutches, using a cane, or pushing a stroller, etc.) would benefit from level boarding the drivers cautioned that they would still not board quickly and that given that the person has a reduced mobility capability drivers would not take off until after these passengers were safely seated. The drivers also noted that dwell times for wheelchair bound passengers will still need to take into account the time it would take to secure the passenger. The consensus from the drivers was that mobility impaired passengers should board through the front doors, so that the drivers can get to the wheelchair bound passengers faster and that drivers can better see when passengers who may have balancing difficulties are seated. The drivers were asked if they felt that it would be necessary to secure the passengers if it wasn’t a legal requirement, as occurs with trains. The drivers felt that it would still be necessary as the motion of buses and trains are very different and they felt that it could present a safety hazard. One driver suggested that if there was a person available on the platform they could potentially secure the wheelchair passengers - however there was general agreement that a person would not be available. The current plan for the Lane County deployment is to have two wheelchair securement bays that face each other (leaving one passenger forward facing and the other rear facing). The BRT project engineer mentioned that they are currently dealing with the issue of how to let a passenger who is not forward facing know that their stop has arrived.

(Inputs from combined workshop, September 3, 2004):

Even though this was determined to not be an element in definition of lane assist system requirements, it was still recognized to be an important issue for the introduction of these systems, and one that needs to be considered as part of the implementation strategy.

There were diverse opinions about how to seek public/rider acceptance of the lane assist systems. Lane Transit prefers to introduce the systems without publicity, and then publicize them after they have been working successfully for a while. AC Transit prefers to introduce them in the environmental review process for their new BRT, as part of the means of mitigating the impacts of the BRT (in right-of-way needs, or elimination of fewer parking spaces).

Recommendations for enhancing the chances for public acceptance included:

- Test the system thoroughly before starting any public fanfare about its introduction.
- If ride quality is good, people are more likely to be favorable.
- Educate the public about driver roles and safety issues.

A focus group study was suggested, using riders and non-riders from the general public, to gauge their reactions. The existing prototype bus system is good enough to use as a basis for demonstrating to people, as long as it is used the way it would be in normal service, without trying to show off more extreme conditions.

2.6 Summary

The workshops with representatives from the four transit agencies combined with studies of the background information about their BRT system plans provided a rich set of information for the development of the needs and the requirements for lane assist and precision docking systems. There were several consistent themes in the comments that were received from the workshop participants:

(a) Lane assist and precision docking systems would indeed be useful in BRT applications. However, different transit properties have different reasons for being interested in lane assist systems, with their primary focuses on different kinds of benefits, and operating under different conditions and cost structures. This tends to lead toward different technical requirements as well. Rather than a single set of requirements, they would prefer to see a matrix that shows which technologies can meet which of several different levels of desired performance under different operating conditions.
(b) All of the transit properties were interested in seeing a more quantitative cost benefit analysis, including the time-saving benefits that could directly affect their operating costs or farebox revenues. They prefer to see the passenger time savings accounted for separately so that this broader societal benefit can be assessed on its own in their boards' investment decisions.
(c) Consideration of institutional issues needs to be focused narrowly on issues specific to lane assist systems, not the broader set of issues associated with BRT in general.
(d) The report needs to be technology-neutral, focusing on the generic requirements derived from needs, rather than on the performance of any specific technology.

The workshops were mostly aimed toward identifying the transit properties' needs for lane assist systems and then identifying how those needs determine the system performance requirements. The workshop participants noted that cost and passenger/ public acceptance should not be classified among the requirements, although they are certainly important considerations in determining whether a system can be deployed.

In addition to the discussions on benefits and costs, requirements and deployment issues, workshop participants felt that the field testing is essential as previous experience suggests that it is not possible to anticipate all the possible occurrences/outcomes, including all the unexpected things that other drivers might do such as cutting in front of buses and blocking bus stops. In addition a demonstration would have the advantage of giving a better picture of the potential speed and travel time benefits of a system.

The need for a large-scale demonstration project was a central theme brought up by the participants throughout the combined workshop. The participants suggested that it should first be done as a closed track test over several months, before exposure to the general public. There was discussion as to whether this could be funded by a manufacturer or the FTA. It was generally felt that no transit agency would want to take on such a demonstration itself yet it would be necessary for a demonstration to be done before transit agencies would consider purchasing the technology.

3.0 Analyses of Needs, Benefits/Costs and Deployment Issues

The discussions by workshop participants provided a rich set of perspectives and inputs toward the needs and requirements studies. The project team synthesized the stakeholders' inputs and, based the inputs, conducted analyses of the needs, benefits and costs and deployment issues.

3.1 Benefits of Lane Assist and Precision Docking Systems

Inputs from four partner transit agencies provide strong justifications for lane assist and precision docking systems, which accrue benefits in many areas, as summarized below.

3.1.1 Enables Buses to Operate Within Narrow Lanes that Facilitate Dedicated BRT Deployment

The most dramatic and quantifiable benefit is derived from the accurate lane tracking capability of the automatic steering control system, which makes it possible to operate the bus in a lane that is only slightly wider than the bus, and therefore considerably narrower than a conventional lane. This ability to operate in a narrower lane offers a variety of advantages:

- Enabling operation of buses in lanes that would otherwise be considered too narrow, such as former rail rights of way, parking lanes on arterials or shoulders on freeways;
- Enabling full-speed operations in locations where drivers would otherwise need to slow down significantly, thereby improving productivity and reducing passenger delays;
- Reducing construction and right-of-way costs for new transitways, especially if these involve the need for costly new tunnels or bridges.

Common width for a regular bus lane is 12 feet, while a guided bus lane can be as narrow as 9.5 feet (the width of the bus is 8.5 feet). This can be a big advantage if land required for the bus lane is currently being used for other purposes such as on-street parking, bike lanes, or landscaping. Narrow lanes can also help to avoid or minimize change of road alignment.

A reduced lane width can sometimes be the difference between a project being approved or rejected if the impact of a wider lane is not feasible from a political or financial standpoint. In the Eugene, Oregon BRT corridor, for example, there was no room for wide lanes in some locations, while in Los Angeles, the city required that the lane width be no greater than 10.5 ft. In such cases, electronic guidance can also be vital in deciding the level of BRT system to be deployed, i.e., Type 3 (exclusive lane BRT) vs. Type 1 (non-exclusive BRT).[3]

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[3] This nomenclature refers to the four types of BRT systems defined by Booz-Allen Hamilton for the Federal Transit Administration.

Note that the significant reduction in lane width applies on straight roadways and roadways with large radii of curvature. However, in tight curves, vehicle geometry requires larger lane widths even with “perfect” steering. For example, with a turning radius of 100 feet, a 40-foot bus needs a lane 3 ft. wider than the bus and a 60-foot articulated bus needs a lane almost 3.5 feet wider than the bus (see details and technical explanation in Appendix A).

3.1.2 Provides Consistent Travel Time, Especially at Bus Stops

A precision docking system can reduce the time needed for passenger boarding and alighting. The actual time saving will depend on many factors, and is likely to have large variability across transit properties, as well as from stop to stop within the same property. The factors that will influence the boarding and alighting times include:

- Low floor or high floor bus
- Fare payment policy (off-board, onboard cash or card)
- Door-use policy for boarding and alighting
- Bus positioning at stop (closeness to curb, presence of obstacles, snow, or running water in gutter, height and condition of curb)
- Weather conditions
- Passenger mix, including proportion of young and agile, parents with children, elderly and frail, people carrying packages, and wheelchair-bound or on crutches.

It is not practical to develop a comprehensive data set to address all of these factors. Precision docking has an obvious direct influence on the bus positioning at the stop, and its potential for time saving will depend heavily on the passenger mix, which is a variable that is impossible to control. In order to focus attention on the effect of precision docking rather than the other influences on boarding and alighting time, we will assume conservatively that it will be applied to low-floor buses. While off-board fare payment and flexible door-use policies can speed up boarding and alighting and can be recommended in general to reduce dwell times at stops, their potential interactions with precision docking are beyond the scope of the current evaluation.

Lane assist systems can create a better operational environment to facilitate faster and smoother turning, lane changing and merging thus increasing the operating speed of the bus by eliminating driver hesitation in making such maneuvers. Additionally, the same guidance technology can be used for precision docking, which facilitates fast boarding and alighting, thereby minimizing dwell time at stops. Precision docking enables the vehicle to consistently pull in very close to the boarding platform. When combined with a boarding platform that is at the same level as the floor of the bus, precision docking can eliminate the need for wheelchair lifts or other similar devices. These features all contribute to reduction of delays for in-line operation and at bus stations, thereby reducing the uncertainties and improving the reliability of transit operation.

3.1.3 Helps to Reduce Overall System Cost

A common width for a regular bus lane is 12 feet, while a guided bus lane can be as narrow as 9.5 feet (the width of the bus is 8.5 feet). The land savings for a two-lane guided busway is approximately 26,400 square feet per mile. Using a land value of $15 per square foot, the cost savings is approximately $400,000 per mile. For example, the estimated right of way cost saving for AC Transit's Telegraph-International BRT system could be up to $15-20 M by applying electronic guidance technologies. Special pavement design (e.g., concrete tracks) will reduce infrastructure cost (AC Transit's example: BRT with electronic guidance can reduce infrastructure construction cost by $10-20 M). Cost savings can increase if the extra lane width required for conventional lanes would displace businesses or damage businesses by removing parking, or if the route requires construction of bridges or tunnels.

Higher operating speeds and less dwell time support improved productivity, which can help transit agencies to reduce the fleet size required for corresponding bus routes. Higher productivity and service quality can help to attract riders and therefore contribute to increased fare box return.

3.1.4 Provide Rail-Like Image and Service

A goal of BRT is to achieve a rail-like image. Lane assist and precision docking systems create a functional equivalent of a fixed guideway much like that of rail. It not only facilitates a rail-like image, but also rail-like efficiency, ride comfort and quality of service. By making it more like rail transit, lane assist and precision docking systems improve the amenity value and status of bus transit. This is particularly difficult to quantify, but in the long term it should be manifested as a ridership increase. In the absence of precision docking, an alternative way of providing the "gapless" boarding of a bus, without passengers having to step across a gap or up a step, would be by deploying the wheelchair ramp for passengers to board from the curb. PATH has measured the time needed to do this on its New Flyer buses, and has found the complete cycle to extend and retract the simplest flip-style ramp to be 30 seconds. This would be a significant penalty to bus travel time, but provides an indication of how this amenity value could be provided in the absence of precision docking.

3.1.5 Helps Reduce Driver Stress

Electronic guidance could reduce drivers' stress level while at the same time improving efficiency and safety. It can free the driver from one of the most demanding tasks, steering, so that she can pay more attention to safety and operating speed as well as customer service tasks. Because electronic guidance only helps rather than eliminates the driver, it is expected to receive positive union acceptance, and when it has been demonstrated to bus drivers it has been received very favorably.

3.1.6 Helps Ensure Mobility and Accessibility

Electronic guidance can improve access to public transit facilities by disabled persons. When combined with a boarding platform that is at the same level as the floor of the bus, precision docking can eliminate the need for wheelchair lifts or other similar devices. It also eliminates the need for stepping up into the bus, which can be difficult for the elderly or persons with mobility impairments.

3.1.7 Enhances Safety

Electronic guidance eliminates driver variations and driver errors in steering, thereby contributing to elimination of crashes involving transit buses. For example, side collision has been one of the most frequently occurring crashes for transit buses, accounting for about 40% of crashes and 30% of crash costs. In contrast, light rail has very low side collision rates because of its well-defined vehicle path. Electronic guidance combined with distinct lane markings will allow other vehicles and pedestrians to clearly see the travel path of the BRT vehicles and to help avoid collisions with buses en-route, at intersections, and at loading zones. The well-defined bus path, together with necessary regulations and law enforcement to minimize parking violations, should eliminate collisions with parked vehicles. Lane keeping and precision docking can also reduce passenger injuries during boarding and alighting as well as bus starting, stopping and turning.

Potential safety effects of lane assist are considered in detail in Section 3.3.

3.1.8 Facilitate Environmentally-Friendly BRT Deployment

The amount of impervious surface can be reduced because the lane width is narrower and only the wheel tracks need be paved. The central four feet of the lane, which is never driven upon, can be a surface such as grass or other ground cover. Compared to a conventional 12 foot bus lane, the reduction in impervious surface is 54 percent, or approximately 68,600 square feet per mile for a two-lane busway. Specially designed bus lanes can also facilitate better water drainage.

3.1.9 Facilitate Incremental and Flexible Deployment

Supporting the incremental deployment nature of BRT, electronic guidance technology can also be deployed a segment at a time. These technologies are much more flexible than rail systems in that they can be re-routed to adjust to new work and housing patterns. Temporary re-routing for road maintenance and crashes is also possible.

3.2 Economic Evaluation

Due to the fact that there is no operational electronic bus guidance system in the United States, many of the benefits and costs are difficult to estimate. However, the project team made attempts to evaluate the economic aspects of lane assist and precision docking systems based on a set of assumptions on the system costs and inputs from the four partner transit agencies. Because the benefits for lane assist and precision docking systems are somewhat different, they are therefore analyzed separately here.

3.2.1 Unit Costs of Electronic Guidance Technologies

The electronic guidance technologies that enable buses to be steered automatically, both at bus stops (for precision docking) and while driving at cruising speed, require the investment in essentially the same elements on the buses and the roadway infrastructure: reference markings to define the desired path of the bus and the following in-vehicle components: lateral position sensors, steering actuator, control computer and driver interface. The reference markings and position sensors can be based on a variety of different technologies, but the other elements are largely unaffected by the choice of technology. At PATH, we have experimented with magnetic, machine vision and GPS systems for the reference/sensing technologies and have found the magnetic system to provide the highest accuracy and robustness, which is particularly critical for the performance needed to provide precision docking. We therefore select magnetic guidance technology as an example system and made assumptions based on our estimate on how much magnetic guidance technology would cost in larger quantities. The current cost of installing the magnetic reference markers is about $10 each, which means that the cost of marking a bus stop is about $500 and the cost per mile of guided transitway is about $10,000. In the future, more efficient automated methods of surveying and installing the magnets should cut these costs in half.

The costs of the in-vehicle components are very sensitive to the number of units produced, particularly because of the need to amortize up-front development costs. We have estimated these costs for two different assumed rates of annual production of vehicle guidance systems (which could include trucks as well as buses). These represent higher costs in the near term, when production volumes are lower, and lower costs in the long term, when the production volumes are higher, as shown in Table 3.1.

Table 3.1 Projected Unit Costs of Lane Assist System

Element	Production of Hundreds Annually (near term)	Production of Ten Thousand Annually (long term)
Steering actuator	$2500	$ 500
Magnetic sensors	$5000	$1000
Computer and interfaces	$5000	$1000
Driver interface	$1000	[included]
Installation/ integration	$ 500	$ 200
Total	$14,000	$2700

3.2.2 Precision Docking Evaluations

The cost-effectiveness of precision docking in the settings for the case studies can be addressed from two different perspectives. On the one hand, after estimating the costs of implementing the docking capability, we can estimate how much time saving would be sufficient to "break even" over the life of the bus. On the other hand, we can estimate several possible credible levels of time saving and determine what their benefit/cost ratios would be. In the absence of hard data on time savings, we bound the problem by approaching it from both directions.

We have estimated the cost per bus of implementing precision docking to be about $14 K in the relatively near term. The infrastructure improvements needed to complement the vehicle improvements are two: installation of reference markings at the bus stops and construction of boarding platforms that will be level with the bus floor. If the reference markers are magnets, their installation will likely cost about $500 per stop (50 magnets at $10 each), and the boarding platform could add another $2000 per stop.

3.2.2.1 Lane Transit District

Lane Transit District is likely to be the first transit agency in the U.S. to implement this technology and so the marginal cost per bus is thus likely to be much larger, on the order of $100 thousand. Moreover, LTD is planning to purchase only five buses for its BRT corridor, so it will not be able to benefit from any production economies of scale.

For the route serving the two-way BRT corridor, there will be 20 bus stops to equip, for a total cost of about $50 K, together with $500 K to purchase lane assist systems for 5 vehicles yielding a total cost of $550 K. LTD's BRT along its current route 11 between downtown Eugene and Springfield, will have 10 bus stops in each direction, with each bus estimated to make 20 stops on its round trip through the corridor.

LTD has said that new hours of operation will match current service. Hours of operation for current service are the following:

- Weekdays: Approximately 5 am through midnight
- Saturday: Approximately 6:30 am through 11:15 pm
- Sunday: Approximately 7:30 am through 8:15 pm

LTD will use either a 10-minute or 12-minute headway during weekdays daytime and 20-minute headways during weekday evenings and on weekends. For purposes of the analysis, we assume a 10-minute headway value during weekdays. Thus, there will be approximately twelve hours per day with an average of 6 buses per hour and an additional five hours with an average of three buses per hour, giving a total estimate of 72 bus round-trips per day. With about 260 weekdays of annual operation, plus a lower level of weekend service, we can estimate an average of approximately 300 annual operating days. Over the course of a year, this corresponds to 26,100 round trips, which will generate 522,000 annual bus stop docking maneuvers at the twenty bus stops (10 bus stops per direction over the 4-mile length of the BRT corridor).

Lane Transit District reports an average operating cost of $78.38 per hour for its buses (Source: National Transit Database 2001 Profile for Lane Transit District), which should be the minimum consideration in the value of time saved by precision docking at the bus stops. However, the value of time of the passengers on those buses should not be ignored. In the absence of hard data on the occupancy of the buses in the Eugene-Springfield Area, we can estimate several different occupancy levels for consideration: 10, 20 or 40 passengers. At a value of time of $10 per hour per passenger, these would add $100, $200 and $400 per hour respectively to the direct LTD operating cost savings.

"Break-even" Analysis

The analysis is based on a discount rate of 7%, and a bus life of 25 years (LTD's current fleet of 40-footers has an average lifetime of approximately 20 years). The BRT vehicle is of composite construction with a stainless steel frame and while LTD hasn't been given a design life by the manufacturer and the agency is hoping to use them for about 30 years, we assume a bus lifetime of approximately 25 years. The total cost of $550 K of implementing precision docking is amortized into an annual cost of $47.2 K. This could be a "break-even" investment based on the following time savings (annually and per bus stop) in Table 3.2:

Table 3.2: Break-Even Bus Docking Time Savings for LTD

Hourly costs	Annual Hours Saved	Seconds Saved per Stop
LTD costs @ $78.38	602.19	4.2
LTD+10 pass. @ $178.38	264.60	1.82
LTD+20 pass. @ $278.38	169.55	1.17
LTD+40 pass. @ $478.38	98.67	0.68

So, even small amounts of time saved at each bus stop from precision docking could be found cost effective, particularly when the value of passenger time savings is added to the direct operating cost savings by LTD. Moreover, note that these break-even time savings per stop incorporate the fact that LTD absorbs the full cost of equipping each of the five BRT buses at a high unit cost, reflecting the small number of buses.

Sensitivity Analysis Based on Assumed Docking Time Savings

We hypothesize several possible levels of time saving to see the sensitivity of the benefits and B/C ratios to these time savings. We have selected values of 5 and 10 seconds per stop as the primary sensitivity estimates, to allow for a mixture of cases in which most travelers save a fraction of a second, while others could save several seconds based on their mobility limitations. In addition, we have included a more extreme case of 30 seconds per stop to represent the “comparable amenity level” associated with deployment of the wheelchair ramp at each stop (recognizing that such a large additional delay at each stop would not be acceptable to most passengers). We have also included the very conservative estimate of only 1 second savings per stop.

Using the same value of time and docking system cost estimates as in the previous analysis, the savings and B/C ratios for these cases are in Table 3.3, which shows consistently large to very large B/C ratios for at least 5 seconds saved per bus stop for all passenger loads.

Table 3.3 Precision Docking Sensitivity Analysis for LTD

Time Saved per Stop (s)	Annual LTD Cost Savings	Avg. Passenger Load	Passenger Savings	Annual Saving Total per Bus	B/C Ratio
1	145 hr = $11.4 K	10	$14.5 K	$25.9 K	0.5
1	145 hr = $11.4 K	20	$29.0 K	$40.4 K	0.9
1	145 hr = $11.4 K	40	$58.0 K	$69.4 K	1.5
5	725 hr = $56.8 K	10	$72.5 K	$129.3 K	2.7
5	725 hr = $56.8 K	20	$145.0 K	$201.8 K	4.3
5	725 hr = $56.8 K	40	$290.0 K	$346.8 K	7.3
10	1450 hr = $113.7 K	10	$145.0 K	$258.7 K	5.5
10	1450 hr = $113.7 K	20	$290.0 K	$403.7 K	8.6
10	1450 hr = $113.7 K	40	$580.0 K	$693.7 K	14.7
30	4350 hr = $340.9 K	10	$435.0 K	$775.9 K	16.4
30	4350 hr = $340.9 K	20	$870.0 K	$1,210.9 K	25.7
30	4350 hr = $340.9 K	40	$1,740.0 K	$2,080.9 K	44.1

3.2.2.2 Los Angeles County Metropolitan Transportation Authority (LACMTA)

Los Angeles County Metropolitan Transportation Authority’s Metro Rapid line along the Wilshire-Whittier boulevards corridor is approximately 27 miles long, with 31 bus stops. Along the portion on Wilshire Boulevard (approximately 16 miles and 20 bus stops), LACMTA has been engaged in a three-stage Demonstration Project:

- Stage I: Between Centinela and Federal -- To measure the effectiveness of an exclusive curbside BRT lane operation during AM and PM peak periods by improving Metro Rapid’s service along this portion of Wilshire Boulevard. Right-turning vehicles may enter the BRT lane and use it as a shared lane prior to the intersection. uses may exit the BRT lane to avoid potential delays caused by right-turning vehicles. This portion of Wilshire Boulevard contains two Metro Rapid stops at Barrington and Bundy Avenues.

- Stage II: Between La Brea and San Vicente -- To analyze potential impacts caused by through traffic diversion to parallel streets due to conversion of a curbside travel lane to an exclusive BRT lane during peak periods. This portion of Wilshire Boulevard contains two Metro Rapid stops at Fairfax and La Brea Avenues.

- Stage III: Between Western and La Brea: Similar to Stage II except that the curbside lanes within this portion of Wilshire Boulevard are 10½ feet wide, narrower than the transit lane standard. Thus, in addition to a through traffic diversion analysis, an electronic guidance system could be considered in this project. This portion of Wilshire Boulevard contains three Metro Rapid stops at La Brea, Crenshaw, and Western Avenues.

For purposes of this case study analysis, we focus on the Stage III site because of its significance to and for LACMTA's potential use of electronic guidance (Korve, 2003).

We use the same methodology as in the Lane Transit District analysis, except, of course, we use parameter values that are appropriate for LACMTA.

Even though we focus only on the 2-mile portion of the Wilshire corridor, LACMTA would need to equip each of its 85 signature red and white Metro Rapid buses serving the entire corridor. Because of the fleet size, we use the estimated cost of $14 K to equip each bus as the production lot size is on the order of 100 vehicles (Table 1) for a total cost of equipping the vehicles of $1,190,000. Again using magnetic referencing, the infrastructure improvements needed to complement the vehicle improvements would cost approximately $2,500 per stop. With six stops per round trip, this yields an additional $15,000 for a total of cost of $1,205,000.

LACMTA's Metro Rapid is in operation between 4 AM and midnight each weekday. Between 4 AM and 7 AM, 10 AM and 4 PM, and 7 PM and midnight headways are 10 minutes. During the two peak periods, 7 AM – 10 AM and 4 PM – 7 PM, headways are 2.5 minutes. Thus, there would be approximately fourteen hours per day with an average of 6 buses per hour and an additional six hours with an average of twenty-four buses per hour, giving a total estimate of 228 bus round-trips per day. With about 260 weekdays of annual operation, plus a lower level of weekend service, we can estimate an average of approximately 300 annual operating days. Over the course of a year, this corresponds to 68,400 round trips. These round trips will generate 410,400 annual bus stop docking maneuvers at the three bus stops per direction over the 2-mile portion of the BRT corridor.

LACMTA reports an average operating cost of $94.83 per hour for its buses (Source: National Transit Database 2001 Profile for MTA), which should be the minimum consideration in the value of time saved by precision docking at the bus stops. Again, the value of time of the passengers on those buses is included and we estimate several different occupancy levels for consideration: 10, 20 or 40 passengers.

"Break-even" Analysis for LACMTA

Using a discount rate of 7%, and a bus life of 15 years, the total cost of $1,205 K for implementing precision docking is amortized into an annual cost of $132.5 K. This could be a "break-even" investment based on the following time savings (annually and per bus stop) in Table 3.4:

Table 3.4 Break-Even Bus Docking Time Savings for LACMTA

Hourly costs	Annual Hours Saved	Seconds Saved per Stop
MTA costs @ $94.83	1397.24	12.3
MTA + 10 pass. @ $194.83	680.08	6.0
MTA + 20 pass. @ $294.83	449.41	3.9
MTA + 40 pass. @ $494.83	267.77	2.3

Thus, large amounts of time saved at each bus stop from precision docking could be found cost effective, particularly when the value of passenger time savings is added to the direct operating cost savings by LACMTA. Since LACMTA's desire is to provide exclusive lanes for its Metro Rapid service, we would expect to see the portion of exclusive bus lanes along the Wilshire corridor to grow — and thus encompass more Metro Rapid bus stops — if only incrementally over the next few years. If the number of Metro Rapid bus stops using precision docking were to double from three in the current case study to six, then the break-even point would be cut in half, reducing such values to levels more consistent with values for boarding and alighting times for Light Rail Transit (Kittelson, 1999).

Sensitivity Analysis Based on Assumed Docking Time Savings

Using the same value of time and docking system cost estimates as in the previous analysis, the savings and B/C ratios for these cases are in Table 3.5, which shows consistently large to very large B/C ratios for at least 10 seconds saved per bus stop for all passenger loads. Once again, the docking function would become much more cost effective as larger portions of the route are equipped.

Table 3.5 Precision Docking Sensitivity Analysis for LACMTA

Time Saved per Stop (s)	Annual MTA Cost Savings	Avg. Passenger Load	Passenger Savings	Annual Saving Total per Bus	B/C Ratio
1	114 hr = $10.8 K	10	$11.4 K	$22.2 K	0.2
1	114 hr = $10.8 K	20	$22.8 K	$33.6 K	0.3
1	114 hr = $10.8 K	40	$45.6 K	$56.4 K	0.4
5	570 hr = $54.1 K	10	$57.0 K	$111.1 K	0.8
5	570 hr = $54.1 K	20	$114.0 K	$168.1 K	1.3
5	570 hr = $54.1 K	40	$228.0 K	$282.1 K	2.1
10	1140 hr = $108.1 K	10	$114.0 K	$222.1 K	1.7
10	1140 hr = $108.1 K	20	$228.0 K	$336.1 K	2.5
10	1140 hr = $108.1 K	40	$456.0 K	$564.1 K	4.3
30	3420 hr = $324.3 K	10	$342.0 K	$666.3 K	5.0
30	3420 hr = $324.3 K	20	$ 684.0 K	$1,008.3 K	7.6
30	3420 hr = $324.3 K	40	$ 1,368.0 K	$1,692.3 K	12.8

3.2.2.3 Alameda-Contra Costa Transit District (AC Transit)

AC Transit is planning to implement a bus rapid transit system along the Telegraph – International Boulevard corridor in the East Bay of the San Francisco Bay Area. The corridor is 18 miles long, with a plan for 33 BRT stops at an average stop spacing of approximately 0.55 miles. “Most” of the 18-mile alignment will have an exclusive transit lane, so, until more definitive and accurate data are available from AC Transit on what portion of the corridor will be an exclusive bus lane, we assume that approximately two-thirds of the corridor will utilize an exclusive transit lane, that is, 12 miles, and this will comprise the corridor portion utilizing precision docking. There are approximately 22 BRT bus stops in each direction within this portion of the corridor.

The new BRT corridor will supplement AC Transit’s current service along routes 40, 51, and 82. We assume that the hours of operation for the new BRT service will closely match these existing local routes, that is, approximately between 5 AM and 11 PM each weekday. Headways for the new service will be 5 minutes during morning and afternoon peak periods and 7.5 minutes during off-peak. Between approximately 5 AM and 7 AM, 9 AM and 4 PM, and 6 PM and 11 PM headways are 7.5 minutes. During the two peak periods, 7 AM – 9 AM and 4 PM – 6 PM, headways are 5 minutes. Thus, there will be approximately fourteen hours per day with an average of 8 buses per hour and an additional four hours with an average of twelve buses per hour, giving a total estimate of 160 bus round-trips per day. With about 260 weekdays of annual operation, plus a lower level of weekend service, we can estimate an average of approximately 300 annual operating days. Over the course of a year, this corresponds to 48,000 round trips, which will generate 2,112,000 annual docking maneuvers at the 22 bus stops per direction over the 12-mile portion of the BRT corridor.

AC Transit has ordered 134 forty-foot Van Hool A330 and 57 sixty-foot articulated AG300 buses. These new buses will appear on AC Transit's Bus Rapid Transit lines, and also will be assigned to at least five major trunk lines. Because of the fleet size, we use the estimated cost of $14 K to equip each bus as the production lot size is on the order of 100 vehicles (Table 1), for a total cost of equipping the vehicles of $2,674,000. Again using magnetic referencing, the infrastructure improvements needed to complement the vehicle improvements will cost approximately $2,500 per stop. With 44 stops per round trip, this yields an additional $110,000 for a total cost of $2,784,000.

AC Transit reports an average operating cost of $101.00 per hour for its buses (Source: National Transit Database 2001 Profile for AC Transit), which should be the minimum consideration in the value of time saved by precision docking at the bus stops. Again, the value of time of the passengers on those buses is included and we estimate several different occupancy levels for consideration: 10, 20 or 40 passengers.

"Break-even" Analysis for AC Transit

Using a discount rate of 7%, and a bus life of 15 years, the total cost of $2,784 K of implementing precision docking is amortized into an annual cost of $305.7 K. This could be a "break-even" investment based on the following time savings (annually and per bus stop) in Table 3.6:

Table 3.6 Break-Even Bus Docking Time Savings for AC Transit

Hourly costs	Annual Hours Saved	Seconds Saved per Stop
AC Transit costs @ $101.00	3026.73	5.2
AC Transit + 10 pass. @ $201.00	1520.90	2.6
AC Transit + 20 pass. @ $301.00	1015.61	1.7
AC Transit + 40 pass. @ $501.00	610.18	1.0

So, even small amounts of time saved at each bus stop from precision docking could be found cost effective, particularly when the value of passenger time savings is added to the direct operating cost savings by AC Transit.

Sensitivity Analysis Based on Assumed Docking Time Savings for AC Transit

Using the same value of time and docking system cost estimates as in the previous analysis, the savings and B/C ratios for these cases are in Table 3.7, which shows consistently large to very large B/C ratios for at least 5 seconds saved per bus stop for all passenger loads.

Table 3.7: Precision Docking Sensitivity Analysis for AC Transit

Time Saved per Stop (s)	Annual AC Transit Cost Savings	Avg. Passenger Load	Passenger Savings	Annual Saving Total per Bus	B/C Ratio
1	587 hr = $59.3 K	10	$58.7 K	$117.9 K	0.4
1	587 hr = $59.3 K	20	$117.3 K	$176.6 K	0.6
1	587 hr = $59.3 K	40	$234.7 K	$293.9 K	1.0
5	2933 hr = $296.3 K	10	$293.3 K	$589.6 K	1.9
5	2933 hr = $296.3 K	20	$586.7 K	$882.9 K	2.9
5	2933 hr = $296.3 K	40	$1,173.3 K	$1,469.6 K	4.8
10	5867 hr = $592.5 K	10	$586.7 K	$1,179.2 K	3.9
10	5867 hr = $592.5 K	20	$1,173.3 K	$1,765.9 K	5.8
10	5867 hr = $592.5 K	40	$2,346.7 K	$2,939.2 K	9.6
30	17600 hr = $1,777.6 K	10	$1,760.0 K	$3,537.6 K	11.6
30	17600 hr = $1,777.6 K	20	$3,520.0 K	$5,297.6 K	17.3
30	17600 hr = $1,777.6 K	40	$7,040.0 K	$8,817.6 K	28.8

3.2.3 Lane Assist Evaluations

The most significant economic benefit from use of lane assist is expected to arise from the ability of the automatic steering technology to operate a bus at full cruising speed in a lane that is only ten feet wide rather than twelve feet wide.

3.2.3.1 Lane Transit District

For LTD’s bus rapid transit system, approximately 65% of the 4-mile corridor will be a dedicated bus-only lane, while the remaining portion will allow buses and non-bus vehicles to mix. Of this 65%, that is, 2.6 miles, approximately 2/3 will be a single bus-only lane that branches out into two parts at each BRT stop and 1/3 will be one lane in each direction. Thus, there will be approximately 3.5 lane-miles along the BRT corridor for which the bus-only lane could be 2 feet narrower than originally planned without the use of the guidance technologies, with significant savings in construction costs. Considering that purely from the point of view of surface area of the construction project, it means that the footprint of the paving could be reduced by about 36,960 square feet.

In contrast, the costs associated with providing the automatic steering control for the buses are essentially the same as for the precision docking described in the previous section, plus the addition of reference markers throughout the length of all lanes of the transitway. With approximately 3.5 lane miles of magnet installations required at $5 K per mile, we have an additional cost of $17.5 K, for a total capital cost of $567.5 K. Note that all but this final $17.5 K was already accounted for in the docking analysis.

"Break-even" Analysis

In this case, we are considering the trade-off between two different capital costs, one for the automatic steering technology and the other for bus lane construction. We are spending $567.5 K for automatic steering systems and reducing the bus lane construction area by 36,960 square feet. Therefore, if the cost of the roadway construction is more than $15.35 per square foot, the investment in automatic steering appears cost effective.

Note that this break-even cost per square foot is dramatically lower than even the cost of suburban residential construction, and probably an order of magnitude lower than the cost of urban residential structures.

3.2.3.2 Los Angeles County Metropolitan Transportation Authority (LACMTA)

For LACMTA's Stage III Demonstration Project in which curbside lane width is 10.5 feet instead of the standard 12-foot lane, the use of electronic guidance technologies would be required to implement the bus-only lane over this 2-mile portion of the Wilshire corridor. The only alternative to use of an electronic guidance system would be to expand the travel right-of-way by approximately 1.5 feet wide and 2 miles long on each side of the 2-way Wilshire corridor, for a total of 31,680 square feet where construction would be required. The task of expanding the roadway by 1.5 feet over the length of 4-lane miles would not be as simple as removing sidewalk, repaving the road, and reconstructing the new curb. There are numerous items that would have to be relocated, some of which having significant parts beneath the ground that would entail time and financial resources to accommodate. These include:

- Traffic signal support poles
- Light posts
- Drainage culverts
- Trees
- Fire hydrants.

Other items would also have to be relocated but not requiring as much time or labor:

- Traffic controllers
- Newspaper stands
- Mailboxes
- Parking meters
- LACMTA's Metro Local bus stops

In contrast, the costs associated with providing the automatic steering control for the buses are essentially the same as for the precision docking described in the previous section, plus the addition of reference markers throughout the length of all bus lanes. With approximately 4 lane miles of magnet installations required at $5 K per mile, we have an additional cost of $20 K, for a total capital cost of $1,225 K. Note that all but this final $20 K was already accounted for in the docking analysis.

"Break-even" Analysis for LACMTA

In this case, we are considering the trade-off between two different capital costs, one for the automatic steering technology and the other for infrastructure-related construction. We are spending $1,225 K for automatic steering systems and avoiding having to pay construction costs over the 31,680 square foot area. Therefore, if the cost of the roadway reconstruction is more than $38.67 per square foot, the investment in automatic steering appears cost effective.

Over the course of the 2-mile portion of the corridor, there are 49 traffic signals, 146 light posts, 20 drainage culverts, 170 trees, and 30 fire hydrants. Without more hard data on the costs of roadway construction and removal/relocation of "street furniture" we cannot make more definitive statements about this tradeoff, but with the sheer number of these individual items requiring substantial investment of resources, it, nonetheless, would appear as though electronic guidance would be cost effective.

3.3 Safety Benefits of Lane-Assist and Precision Docking Systems

Lane assist technologies offer a number of safety benefits to transit services, particularly those utilizing Bus Rapid Transit systems. These benefits are brought about through the following safety enhancements:

(a) Mitigation of certain types of vehicle collisions: Since the lane assist function eliminates driver variation and driver error in steering, it can contribute to reducing many crashes involving transit buses. Specifically, lane assist combined with distinct lane markings allows other vehicles and pedestrians to clearly see the travel path of the BRT vehicles and avoid collisions with these buses en route, at intersections, and at loading zones. Additionally, as has been shown with light rail operations, a well-defined bus path, combined with necessary regulations and law enforcement to minimize parking violations, will eliminate a large number of side collisions, collisions with pedestrians and collisions with parked vehicles.
(b) Reduction of the likelihood of passenger injury during boarding/alighting: Precision docking, combined with low-floor buses and boarding platforms, virtually eliminates the need to step over a gap or step up when boarding or alighting, thus removing two significant sources of boarding/alighting incidents.
(c) When using lane assist, starting, stopping and turning can be smoother than under manual control, which can reduce passenger injuries due to falls while the bus is moving
(d) Improvement of driver's responsiveness to travel environment and on-board passenger activities: The application of lane assist relieves the driver of one of his/her most demanding tasks, allowing increased attention to be paid to other safety and operational critical tasks such as longitudinal control, obstacles in front of and around the bus, and in-vehicle passenger activities.

While benefit (d) is relatively difficult to quantify, benefits (a)-(c) can be studied by analyzing crash data involving transit buses. In a transit Intelligent Vehicle Initiative project also sponsored by FTA, PATH made such an analysis utilizing crash records and cost data from 35 California transit agencies for a five year period.

Because lane assist technologies can provide “rail like” features to BRT systems, a parallel study of the incident data for one light rail system was conducted. The goal of this comparative study was to evaluate the statistics and characteristics of incidents for the two type of systems and, based on assumptions that vehicles and pedestrians would treat buses equipped with lane keeping functions in a manner similar to light rail, to draw some conclusions as to what extent these collisions and passenger injuries can be prevented and the severity of crashes or injuries can be reduced by introducing lane assist capability.

3.3.1 Incident Data Analysis for Transit Buses

The review of 35 transit agencies in California revealed that in a five year-period, a total of 5,255 collisions and 4,285 non-collision incidents occurred. The total cost was recorded as $38,467,083, of which the costs for collisions, non collision incidents and ADA violations were $22,351,980, $13,583,367 and $2,531,736 respectively.

3.3.1.1 Vehicle Collisions by Scenarios

Among collisions, a few involving severe injuries accounted for a large percentage of the costs. Specifically, there were a total of 23 serious casualties with a total cost of $8,346,264, which accounted for 0.65% of claims and 52.04% of costs for all collision incidents. The table below lists all of the severe casualties, including 12 frontal, 5 side, and 6 of unknown initial point of contact (POC) collisions.

Table 3.8 Collisions with Severe Injuries

No	POC	Cost	Incident Type
1	S	$195,000	Intersection, going straight bus hit a right turning vehicle
2	F	$162,500	Intersection, bus failure to yield right of way
3	S	$203,300	Sideswipe, bus changing lane
4	F	$130,044	Bus struck a standing vehicle
5	S	$104,726	Bus struck a standing vehicle
6	F	$132,456	Bus rear-ending another vehicle
7	F	$121,335	Bus rear-ending another vehicle
8	F	$127,427	Bus rear-ending another vehicle
9	F	$236,615	Bus rear-ending another vehicle
10	F	$350,639	Bus rear-ending another vehicle
11	F	$172,448	Bus rear-ending another vehicle
12	S	$267,222	Bus pulling from loading zone
13	F	$302,307	Collision, detail unknown
14	N	$258,904	Collision, detail unknown
15	N	$163,542	Bus striking a pedestrian
16	N	$429,636	Bus striking a pedestrian (fatal)
17	S	$1,997,950	Bus striking a pedestrian
18	N	$906,024	Bus striking a pedestrian
19	F	$250,000	Bus striking a pedestrian
20	F	$975,000	Bus striking a pedestrian (fatal)
21	F	$298,014	Bus striking a pedestrian
22	N	$106,674	Bus striking a pedestrian
23	N	$454,491	Collision, detail unknown (fatal)
Total		$8,346,2634	

- *POC: initial point of impact.*

Two collision scenarios stand out from the others as sources of serious casualties: “Bus striking a pedestrian” (8 claims with 3 front, 1 side and 4 not-known initial point of impact), and “bus rear-ending another vehicle” (6 claims, all front). They account for 60.9% of claims and 75.1% of cost among all serious casualties.

In addition to the 23 serious injury collisions listed above, a total of 3,184 vehicle collisions were recorded in 5 fiscal years for 34 agencies, with a total cost of $6,768,819. The following eight collision scenarios have been identified.

Table 3.9 Collision Scenarios

Collision Scenario	Definition
S1	Intersection collision
S2	Bus rear-ending another vehicle (frontal collision)
S3	Collision at bus rear, including bus backing up (rear collision)
S4	Bus hit a standing vehicle
S5	Sideswipe (side collision)
S6	(Other vehicle) Cut-in collision
S7	Loading zone incident
S8	Collision between two buses
S9	Other vehicle collisions

Five scenarios: intersection collision (S1), bus rear-ending another vehicle (S2), bus hitting a standing vehicle (S4), sideswipe (S5), and collision between two buses (S8), account for 68.43% of claims and 72.9% of costs among all vehicle collisions. This is shown in Figure 3.1.

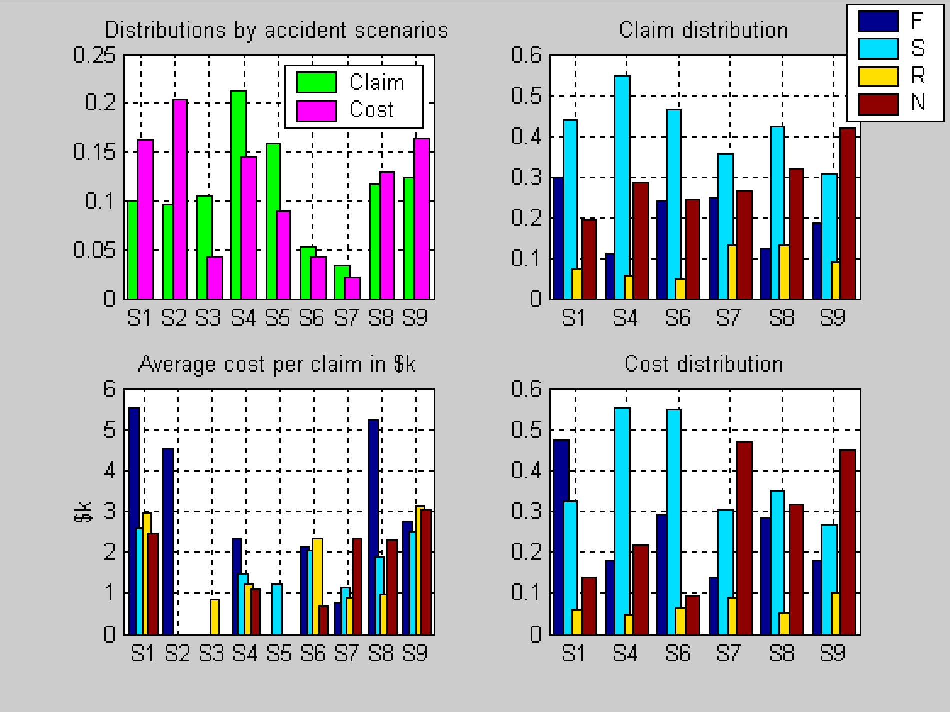

Figure 3.1 Vehicle Collisions by Collision Scenario in Five Fiscal Years

Twenty-one percent of intersection collisions (S1) occurred while the bus was going straight (15% of costs), while 11% and 18% occurred while the bus was turning right or left (4% and 36% of costs), respectively. The scenario “Bus turning left and hitting another vehicle" (as opposed to being hit) stands out from the others (4.4% of claims and 22.3% of costs among all intersection collisions).

Thirty-six percent of sideswipes (S5) occurred while the bus was passing another vehicle (40% of costs), while 45% occurred when another vehicle was passing the bus (30% of costs). The scenario "Scrapes at bus corners" stands out from the others (15% of claims and 25% of costs among sideswipes). This verifies the fact that buses have a wide turning radius, which often makes it difficult to avoid other vehicles.

Most standing vehicle (S4) and cut-in collisions (S6) are side collisions. Thirty percent of loading zone collisions (S7) occurred while the bus was pulling away from the loading zone, accounting for 45% of cost. Two crash scenarios stand out from the others as sources of loading zone collisions: "bus pulling out from zone and hitting a moving vehicle" (16.5% of claims and 32.7% of costs), and "bus pulling into zone and hitting a standing vehicle" (8.3% of claims and 10.5% of costs).

3.3.1.2 Passenger Injuries by Bus Maneuver

For the 35 agencies, there were a total of 4,285 passenger injury incidents during the five fiscal years with a total cost of $13,583,367, and they account for 44.9% of claims and 37.8% of costs among all incidents. The following eight bus maneuvers prior to an incident are considered:

Table 3.10 Passenger Injury Bus Maneuvers

Bus maneuver	Stand for
M1	Bus boarding
M2	Bus alighting
M3	Bus starting
M4	Bus stopping
M5	Bus turning
M6	Bus going straight
M7	Bus moving (others)
M8	Others

Thirty percent of passenger injuries occurred at loading zones (boarding and alighting), which also accounted for 21% of all injury costs. Twenty percent of passenger injuries occurred as the bus stopped; this type of passenger injury has the highest severity as shown in Figure 3.2.

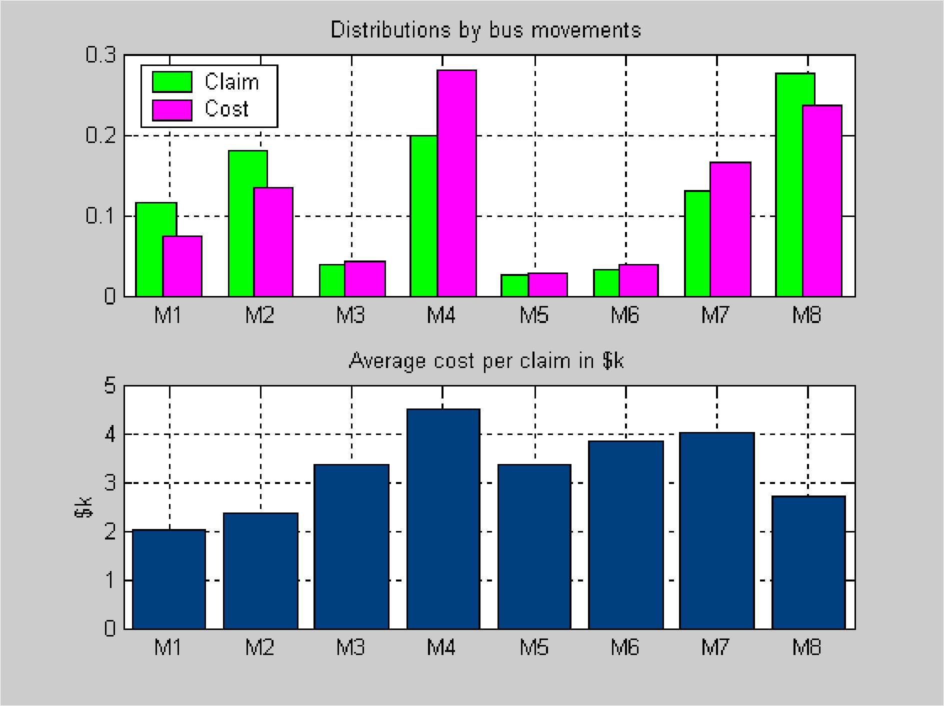

Figure 3.2: Passenger Injuries by Bus Maneuver in Five Fiscal Years

3.3.1.3 Comparison with National Incident Data

The statistics from this analysis have a good match with the national bus incident statistics documented in *Traffic Safety Facts 2000* (NHTSA, 2001) which includes intercity transit and school buses. The incident data for the 35 California agencies shows:

- 26.4% of collisions were frontal collisions, 54.6% were side and 19% were rear collisions while NHTSA reported 28.2% front, 47.6% side and 22.9% rear (excluding the collisions with unknown initial point of impact)
- 92.1% of collisions involved another motor vehicle, 5.1% involved an object and 3.7% involved pedestrians, while NHTSA reported 83.5% with vehicles, and 16.2% with an object.
- 0.65% of collisions involved serious casualties; among them 52.2% were frontal and 21.74% were side collisions. The national data reported that 0.6% of all crashes involved fatalities, among which 68.4% were front related and 16.8% were side related collisions.

3.3.2 Incident Data Analysis for Light Rail Transit (LRT)

During the five years period (from July 1, 1997 to June 30, 2002), there were a total of 362 light rail claims with a cost of $1,262,875 for one agency. These claims are separated into three groups:

1. Collisions, where a collision occurred between a light rail vehicle and another party, i.e., a motor vehicle, an object or pedestrian.

2. Passenger injury, where a light rail passenger was injured on boarding, alighting, or on board (not caused by a collision).
3. Other claims, where there was no collision or passenger injury involved. For example, a vehicle broke a light rail gate, a crossing arm came down on a vehicle, or a pedestrian fell while trying to catch a light rail train.

Table 3.11 Incident and Cost Data For Light Rail (5 Years)

Collision		Passenger injury		Others		Total	
Claims	Cost	Claims	Cost	Claims	Cost	Claims	Cost
112	$191,575	202	$1,056,312	48	$14,988	362	$1,262,875

The initial point of impact information has been obtained by reviewing the original driver reports and police reports for collisions. Four possibilities are considered for the initial point of impact: front (F), side (S), rear (R), and not-known (N).

3.3.2.1 LRT Fatalities

There were three fatalities in the five year period, but no fatality was the fault of the light rail vehicle's driver. The fatalities are listed in the Table below.

Table 3.12 LRT Fatalities in Five Fiscal Years

Number	Cost to Agency ($ K)	Incident description
1	$20	Vehicle flipped onto light rail tracks
2	$466	Passenger stepped in front of a light rail vehicle
3	$2	Pedestrian jumped to death

3.3.2.2 LRT Severe Incidents

There were a total of nine severe (i.e., cost more than $10,000) incidents in the five year period, with a total cost of $1,075,269,which accounted for 85.1% of all incident costs. Four out of the nine severe incidents involved a collision. Among them, two were collisions with vehicles, and two involved collisions with pedestrians. The other five severe incidents involved passenger injuries. Among them, one was injured on boarding, two on alighting, and the remaining two were injured on board. The cost and incident details are listed in Table 3.13.

Table 3.13 Severe LRT Incidents in Five Fiscal Years

Number	Initial point of impact	Cost	Incident description
1	F	$20,506	Light rail hit a car making a left turn in front
2	F	$67,248	Light rail hit a car making an illegal left turn in front
3	F	$12,138	Light rail hit a pedestrian walking on red light
4	F	$41,309	Light rail hit a construction worker
5	Not a collision	$23,550	Passenger injured on boarding
6	Not a collision	$27,845	Passenger injured on alighting
7	Not a collision	$42,027	Passenger injured on alighting
8	Not a collision	$40,052	Passenger hand cut on board
9	Not a collision	$800,595	Passenger head cut on board
Total		**$1,075,269**	

3.3.2.3 LRT Collisions

Excluding the fatality incident and four other severe collisions, there were a total of 107 collisions in the five fiscal years with a total cost of $50,354.

(a) Collisions By Initial Point Of Impact

Seventy-nine percent of collisions were vehicle collisions, while 19% and 2% were pedestrian collisions and stationary object collisions, respectively. These three types of collisions accounted for 76%, 23% and 1% of collision costs respectively as shown in Figure 3.3.

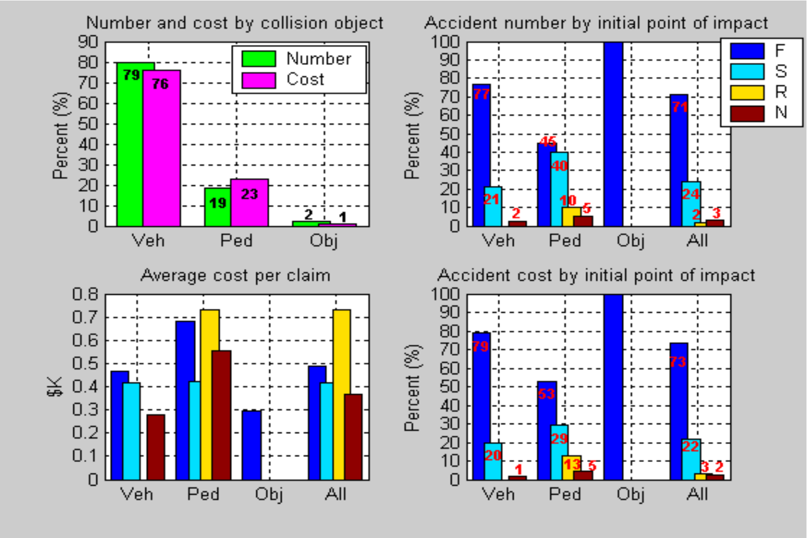

Figure 3.3 General LRT Collision Incidents by Initial Point Of Impact

Seventy-one percent of collisions were frontal, 24% were side, and 2% were rear collisions. The point of impact of the remaining 3% are unknown. Frontal, side, and rear collisions accounted for 73%, 22% and 3% of costs, respectively. On average, each pedestrian collision cost $576, each vehicle collision $450, and each stationary object collision $296.

Thirty-one percent of side collisions were pedestrian collisions, while 86% of frontal collisions were vehicle collisions.

Among the twenty pedestrian collisions, nine (45%) were frontal collisions, which most often were pedestrians walking across the track in front of a light rail train; and eight (40%) were side collisions, which most often were pedestrians walking into the side of the light rail car at the platform.

3.3.2.4 LRT General Vehicle Collisions

There were a total of 85 other vehicle collisions, with a total cost of $38,239 in the five years. They accounted for 79% of the total number of collisions and 76% of costs for collisions. Most vehicle collisions (91% of claims and costs) occurred at intersections, where other vehicles often try to cut in front of the light rail train.

Among the eight non-intersection collisions, two involved a light rail vehicle hitting a standing vehicle (all side); five involved other motor vehicles trying to turn into the light rail right of the way (all front); and the other one was a vehicle rolling back into a light rail car at a station (front). Table 3.14 summarizes the costs for LRT intersection collisions by collision scenario.

Table 3.14 LRT Intersection Collisions in Five Fiscal Years

Collision scenario	Initial point of impact	Collision number	Collision cost
Vehicle turns in front of LR going straight	F	53	$27,320
Vehicle hits side of LR going straight	S	15	$5,979
Vehicle turns in front of a right turning LR	F	6	$609
Vehicle hits side of a left turning LR	S	1	$241
Details unknown	N	2	$552
Total		77	$34,701

3.3.2.5 LRT Passenger Injury

Excluding the two fatalities and the five severe passenger injuries, there was a total of 195 passenger injuries, which cost a total of $121,776.

Thirty-seven percent of passenger injuries occurred during boarding and alighting, 34% on board a moving light rail train, and 26% at the platform (station). Table 3.15 summarizes the injury costs by incident scenario.

Table 3.15 Passenger Injuries in Five Fiscal Years

Injury scenario	Claim	Percent	Cost	Percent
Boarding	29	14.9	$15,078	12.4
Alighting	43	22.1	$31,062	25.5
Fell starting	19	9.7	$5,283	4.3
Fell stopping	11	5.6	$11,871	9.7
Fell turning	1	0.5	$560	0.5
Fell running straight	6	3.1	$9,730	8.0
Fell on board, detail unknown	7	3.6	$5,364	4.4
On board, cut by door	9	4.6	$4,869	4.0
On board, others	14	7.2	$4,095	3.4
Injuries on platform (station)	56	28.7	$33,863	27.8
Total	**195**	**100.0**	**$121,776**	**100.0**

3.3.3 Observations

The analysis shows that light rail incidents have significantly different characteristics from those of traditional transit bus incidents, both in pattern and severity. The primary reason is that light rail runs along a track and can only make contact with another entity that is blocking it in front or is too close to its track.

In the five fiscal years, there were a total of 362 light rail claims for a total cost of $1,262,875. The same transit agency also operates transit buses. In the same time period, it had 1,739 bus collisions (cost $6.3 million) and 1,399 passenger injuries (cost $3.4 million).

Thirty-one percent of light rail incidents were collisions, accounting for 15% of costs. Fifty-six percent of the incidents were passenger injuries on boarding, alighting, on board, and on the platform, accounting for 84% of costs. Thirteen percent of incidents, for a total of 1% of cost, were not collision or injury related. For the same transit agency, 55% of transit bus incidents were collisions (65% of costs) and 45% were passenger injuries (35% of costs). Compared to bus incidents, light rail has a much lower percentage of collisions.

Seventy-nine percent of light rail collisions were vehicle collisions (76% of costs), 19% were pedestrian collisions (23% of costs), and 2% were stationary object collisions (1% of costs). For the same agency, 91% of transit bus collisions were vehicle collisions (82% of costs), 3% pedestrian collisions (12% of costs), and 6% stationary object collisions (6% of costs). Light rail had fewer vehicle collisions for a number of reasons, including the fact that the surrounding traffic is often physically separated from the light rail train and that even when not separated, drivers are more cognizant of the right of way of the light rail train.

The top five vehicle collision scenarios for transit buses were, from the highest to lowest priority (severity):

- bus rear-ending another vehicle (10% of claims and 23% of costs)
- intersection collision (14% of claims and 18% of costs)
- collision between transit buses (8% of claims and 9% of costs)
- standing vehicle collision (18% of claims and 13% of costs)
- sideswipe (16% of claims and 10% of costs)

In comparison, 91% of light rail collisions and costs involved crashes at intersections, which most often involved a vehicle making a turn in front of a light rail vehicle. No collisions in the five year statistics were caused by a light-rail train sideswiping another vehicle.

Because the total travel miles and passenger volume are not available, it is difficult to do a direct comparison of the overall statistics between incident data for buses and light rail. However, the average cost per incident was much lower for light rail than for buses. Excluding the severe incidents, the average costs per collision for light rail and for buses were $450 and $3,620 respectively. The average costs per passenger injury incident for light rail and buses were $650 and $2,430 respectively.

This comparative analysis of the incident data for both transit buses and light rail supports the suggested safety benefits that a guided system can offer. Particularly, the low side collision rate for light rail suggests that guided buses, in conjunction with a clearly identified and marked bus travel lane, can cause other drivers to maintain a higher degree of vigilance when traveling next to dedicated transit lanes, which could decrease encroachments into these lanes. The dedicated lane markings can also help to prevent unintentional placing of vehicles and obstacles in the bus path. The level of benefits would be even greater if the lane-assist function were deployed in an exclusive dedicated lane.

The deployment of precision docking, which will make bus boarding and alighting as convenient as passenger movements on train-type platforms, will lead to significant benefit to passenger safety and operator liability concerns. This portion of direct liability and indirect costs, such as loss of operation time and manpower, is expected to be mostly eliminated or, at least, greatly reduced, with the implementation of precision docking.

Lane assist that delivers smooth lateral motions during in-lane operation can also help to reduce the number and cost of on-vehicle passenger injuries. The safety benefit due to reduced driver stress is not quantifiable at this time. Further human factors studies are needed.

3.4 Deployment Issues

In order to further understand the issues associated with deployment of lane assist and precision docking systems, a study of the institutional issues was conducted using Lane Transit as a case study example. There are several institutional stakeholders, in addition to Lane Transit District, participating in the planning for and design and deployment of bus rapid transit in the Eugene-Springfield area of Oregon. They include the following organizations:

- Lane Council of Governments (LCOG, the Metropolitan Planning Organization)
- Oregon Department of Transportation (ODOT)
- City of Eugene
- City of Springfield
- Lane County.

LTD's Board of Directors has given the other public agencies, apart from LCOG, veto power over the project. The remaining four agencies were represented on the BRT Steering Committee and the Technical Advisory Committee. Staffs from these agencies have been very closely involved in the planning and design of LTD's BRT system. While there are other local, regional, and state organizations and institutions such as the University of Oregon and law enforcement agencies also participating, these other organizations have been part of the outreach program, however, have not been formally part of the decision making structure. Where the project impacted a particular institute or organization, LTD met with their decision makers.

With respect to LTD's organizational and institutional partners, multi-organizational coordination and communication among them has been essential to the success thus far of the BRT project. In particular, staff and elected officials must be fully informed at all times.

With such an array of organizational stakeholders, it is not surprising and almost expected that there would be challenges integrating different and potentially conflicting priorities, objectives, and agendas among the organizations participating in the development of the BRT system. In the case of LTD, there have been numerous occasions when the competing objectives of the participating organizations have conflicted. Probably the biggest has been the perception that transit is being favored above the private-owned passenger automobile, and that scarce right of way is being allocated to transit, which at some future date may be needed for auto lanes/capacity. This issue has been resolved by arguing that transit has a higher potential carrying capacity and that while LTD's BRT plans would not impact existing automobile capacity, there may be an impact on options to provide future automobile capacity through roadway widening.

The planning and design for LTD's bus rapid transit system has also required greater levels of coordination between and or among different groups inside LTD. Some departments within the organization have had concerns about BRT as the future operating solution. These have ranged from the complication of adding a new type of vehicle to the mix to requiring passengers to walk further to stations.

There has also been resistance to LTD’s bus rapid transit system from certain groups that needed to be addressed. The largest resistance to the project came from an environmental group that does not support the regional transportation plan, “Tranplan”, of which BRT is a main strategy. Their resistance to LTD’s BRT system was likely to have been less opposition to BRT specifically, but more as an avenue to oppose the regional transportation plan in general in order to have it redrafted. LTD worked carefully with decision makers through the issues that were raised to overcome this resistance.

Another institutional issue that Lane Transit District has had to deal with is the new vehicle procurement process. The new vehicle purchase has been challenging, with the primary issue being that among LTD’s requirements is a vehicle with doors on both sides, together with a non-standard bus look that is also environmentally friendly.

The success of BRT, as with nearly any new product, depends largely on how well it is “sold” or marketed to the public. This often requires setting high, yet realistic, expectations that are crucial to gain support for BRT. Failure to produce what was promised could lead to disappointment and a loss of public confidence and support. BRT may also require a significant public education campaign on interacting with new transit strategies and technologies such as bus lanes, signal priority systems, queue jump lanes, and new fare collection systems. In this area, LTD has used public meetings and gatherings to discuss its BRT system. LTD has also used direct marketing approaches by mailing information to property owners along the route, including businesses. LTD has unveiled the new system’s name on a communitywide basis by means of newspaper ads and other media outlets.

Relative to its riders, LTD’s reputation in terms of the service it delivers is very positive, with considerable excitement generated toward the deployment of the bus rapid transit system.

One may generally classify an agency’s attitude toward the deployment of new transit technologies, such as electronic guidance systems, in one of three ways:

1. An early adopter
2. Take a wait-and-see attitude at least initially, basically saying “show me the benefits first and I’ll believe it when I see it”, i.e., waiting to make sure the technology is safe and reliable
3. Thus far putting implementation of technology at arm’s length and waiting until new systems or infrastructure become much more standardized across the industry and more affordable.

LTD considers itself to be in the third category, to the surprise of the project team, however necessity has forced it to take more of the initiative and leadership role on a number of BRT issues.

BRT in general, and electronic guidance systems in particular, may also have an impact on a transit agency's employees, especially bus drivers and maintenance workers, relative to the use of new technologies, potential changes in job tasks, and a need for specialized training for new tasks and responsibilities. LTD's strategy has been to involve as many staff members as possible in its BRT project and to provide opportunities for employee input to be solicited to help resolve any such issues. For example, approximately on a quarterly basis, "all-hands" meetings are called to raise, discuss, and resolve such issues. Similarly, input is solicited at smaller venues, such as at individual departmental staff meetings.

Transit electronic guidance systems will involve new procedures, new technologies, and new personnel tasks, so the potential exists for system components not to function as anticipated. It is important to consider how such systems may change the assignment of risk and responsibility should a malfunction occur, as well as the assignment of liability in case of a crash or malfunction. In the context of LTD's BRT system, it is unlikely that any bus would be put into revenue service unless LTD was convinced that it functions safely and operates according to specification. Provided the bus satisfies these requirements, LTD is not opposed to change.

New legislation or changes in existing laws may be needed to implement and operate electronic guidance systems. Elements that may need to be addressed include the legal authority allowing bus drivers to take their hands off the bus' steering wheel, to enforce lane occupancy levels (bus only) (restructure the use of the facility to specific groups or vehicles), and to use automated enforcement techniques. Consistency with policies and procedures of FHWA, FTA, and other federal agencies should also be checked. As electronic guidance systems are relatively new, LTD is not likely to market such systems as machine- driven systems, rather, more as driver-assist systems to help the driver operate in narrower rights-of-way. Once guidance systems become more widely implemented and accepted, then LTD would consider legislation that allows the driver to take his/her hands off the wheel.

Compatibility with existing infrastructure in terms of both roadway markings and material will need to be maintained. New roadway markings must not confuse other drivers so drivers would need assistance to show where the bus should go. Use of different materials such as asphalt and concrete for lanes will need to be determined. Clearly differentiating the BRT facility is critical to the operation of the facility. This can be achieved by a combination of pavement markings and color, lane separators and signage. The most difficult area of conflict occurs where you have driveways on the other side of the BRT facility. Providing clear and unambiguous instructions to the drivers of all other vehicles is critical in this situation.

Consistency with local area plans is necessary for any project, whether BRT or not. While there have not been any special factors associated with LTD's BRT system that has made this consistency more challenging than for other projects, one of the first steps LTD undertook in developing its BRT project was to make sure that the project was integrated with and referenced in the regional transportation plan. Having LTD's BRT project in the plan, a significant and publicly available document, assisted LTD in dealing with local issues.

When light rail transit trains pass through at-grade intersections where other modes cross or at a simple intersection that the LRT train crosses, the train gets priority and signal preemption goes into effect until the train passes through. Currently, plans call for LTD BRT buses to get signal priority — not pre-emption — upon approach to the signal for an early or extended green light. Oregon state law currently prohibits the use of signal preemption for buses. LTD has attempted, unsuccessfully thus far, to argue to the state that the operating characteristics of BRT are more akin to LRT, and thus to have state law changed. Once the system is operational the state may be willing to re-visit the issue. Nonetheless, LTD did get one major approval and that is to use LRT signal aspects on the BRT line. Signal preemption would give LTD the opportunity to phase skip and hold signal phases longer and so provide the BRT greater operational benefits.

3.5 Summary

The study of needs, benefits and costs and deployment issues revealed that lane assist and precision docking systems offer significant benefits over traditional buses. In addition to the capability of operating buses within narrow lanes, which offers the most dramatic and quantifiable benefits for enabling a higher quality and lower cost BRT system, lane assist systems also offer a significant number of subtle and less readily quantifiable advantages including higher operation reliability, improved mobility and ride quality for passengers, reduced stress for drivers and enhanced image for the transit agency. The economic evaluation revealed that the precision docking functions offers large benefit-cost ratios with even small amounts of time saved at each bus stop. The lane assist system can offer even greater benefits from the reduction of the cost of the roadway construction due to narrow lane width.

The safety analysis based on extensive collision data for both transit buses and light rail revealed that light rail incidents have significantly different characteristics from those of traditional transit bus incidents. This analysis suggested that that should BRT buses operate in similar manner to light rail, many incident types involving traditional transit buses, such as side collisions and passenger injuries, could be avoided. Subsequently, there will significant cost savings due to the reduction of these incidents.

The study team also conducted a detailed study on deployment issues associated with LTD BRT system and have identified a number of institutional and deployment challenges.

4. Development of Requirements and Specifications, Measures of Effectiveness and Safety Analysis Methods

Based on the inputs from the stakeholders, the project team conducted studies of the system functional, performance and technical requirements for lane assist and precision docking systems and developed (1) functional requirements, (2) technical specifications, (3) Measures of Effectiveness and (4) safety analysis method for lane-assist and precision docking systems.

4.1 Functional Analysis of Lane Assist and Precision Docking Systems

4.1.1 Functional Blocks of Lane-Assist Systems

The components needed for implementing lane-assist and precision docking functionalities depend on the type of application and the level of interactions among drivers, vehicles, and infrastructure. Figure 4.1 depicts the functional block diagram for lane assist and precision docking systems. When a vehicle is operating in an open environment, sensors generate signals with noise from the background. The sensor outputs are provided to the algorithms or the processing unit for various purposes, such as diagnostics about the system state, or the determination of vehicle location, or the control command to be sent to the actuator. If equipped, a communication system can transmit and receive information from other systems (vehicles or infrastructure) to the processing unit. The information from the processing unit is then fed into a human-machine interface to alert or indicate to a driver the existing threats. Additionally, the output can be fed into actuators to control the vehicle to follow a desired trajectory. In either case, the actions taken by the actuators or the drivers will alter vehicle dynamics, which is further fed back into the loop for sensing and processing.

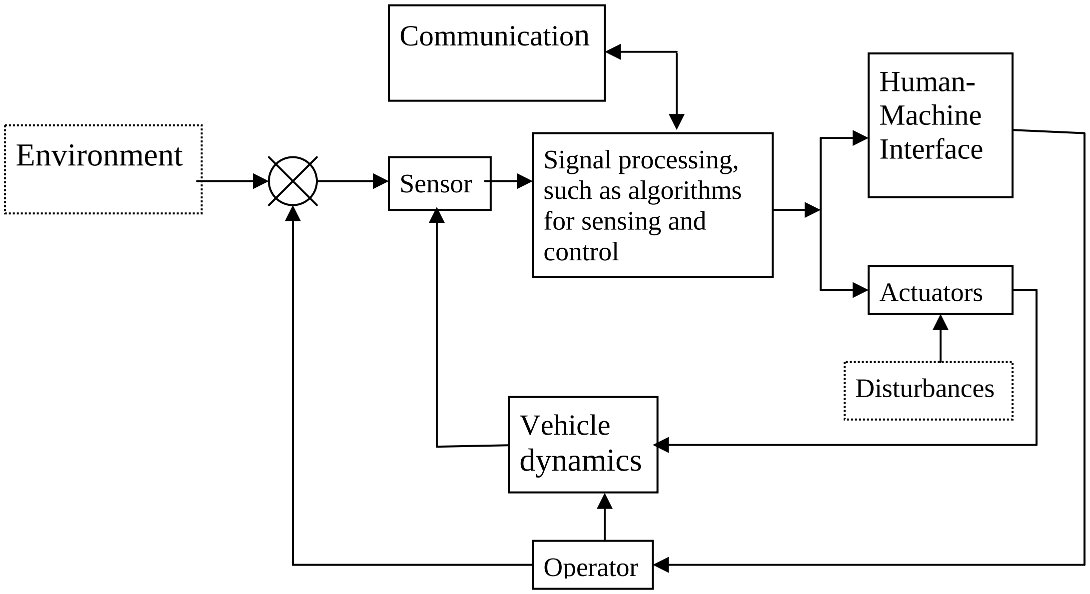

Figure 4.1 Functional Block Diagram of Lane Assist and Precision Docking Systems

Abstractly, in terms of information flows among sub-systems, the system contains the following types of elements:

- Information sources, such as roadway and lane markings, and vehicle motions.
- Information transmitters and receivers (transducers), such as sensors
- Information processors, such as hardware and software for signal processing
- Information representation, such as human-machine displays
- Information executors, such as actuators or operators
- Information channels, such as interfaces among various elements.

Note that both lateral and longitudinal control may exist individually or simultaneously. For example, in the lane-keeping application, drivers may still control the vehicle speed while the lane assist system is regulating the vehicle trajectory by controlling the steering inputs. In the precision-docking mode, the lane assist system may be under automated control without driver inputs.

4.1.2 Functional Decomposition

Depending on the design features and functional requirements of lane assist and precision docking systems, there can be significant variations in the selection of sub-systems and components. For an exemplar case study of lane assist systems, the main functioning blocks are:

i) Vehicle and lane position sensing: Identifying the location of vehicle relative to the infrastructure

The actual sub-systems for this function are determined by the selection of technology. For example, a computer-vision technical approach will require a camera and image processing with clear lane markings on roadways. A magnetic marker system will require the installation of magnets on the roadways and magnetometers on the vehicles for detection and processing. An approach using global positioning systems (GPS) will demand an on-board Differential GPS unit and a geometric map of the roadway.

ii) On-vehicle sensing and processing: data gathering and processing

The components in this category potentially consist of computers or processors, vehicle inertial navigation systems (INS), networking or communication links between sub-systems, and computations required for generating information for driver assistance or commands for controlling functions.

iii) Actuation

If steering or speed control is part of the lane-assist application, then actuators will be needed. The actuation can be implemented electrically, hydraulically, or pneumatically.

iv) Driver-Vehicle Interface (DVI)

The DVI is the bridge or communication channel between drivers and vehicles. It can serve multiple functions, including diagnostic, driver assistance, or actuation.

v) Data Communication Networking

The data communication network exchanges data among all functioning blocks and through channels of communication.

Each of the five blocks can be further decomposed by their functions:

Sensing can be separated into:
- Vehicle lateral position sensing
- Vehicle longitudinal location sensing
- Vehicle speed sensing
- Acceleration sensing
- Yaw rate sensing
- Throttle position sensing
- Brake line pressure or brake stroke sensing

Processing can be separated into:
- Vehicle position processing
- Vehicle state and fault detection processing
- Warning and display signal processing
- Acceleration command processing
- Braking command processing
- Steering command processing

DVI can be separated into:
- Monitoring, indicating the state of vehicular systems
- Signal of impeding automated functions, indicating actions or problems with the control process
- Warning of hazardous situation
- Request for input or intervention by the driver

Actuation can be separated:
- Steering control
- Engine control
- Braking control

Networking can be separated into:
- Networking between sensors and processor
- Networking between processor and DVI
- Networking between processor and actuator

4.2 Preliminary Functional Requirements for Lane Assist and Precision Docking Systems

Based on the inputs from transit stakeholders and the PATH's knowledge gained through development of technologies for transit lane assist and precision docking, preliminary functional requirements were developed. These requirements are grouped into six interrelated areas, including:

- Performance
- Safety
- Reliability
- Availability
- Maintenance
- Compatibility with existing infrastructure

4.2.1 Performance Requirements

Performance can be judged within three broad categories: ride comfort, tracking accuracy, and ease of operation. Ride comfort is essentially the smoothness of steering and, if the system is equipped with speed and braking control, smoothness of acceleration and deceleration. Because of the functional differences between lane assist and precision docking systems, their performance requirements are defined separately.

4.2.1.1 Precision docking performance

4.2.1.1.1 Docking accuracy

Docking accuracy has two criteria, lateral stop accuracy (horizontal gap between docking station and vehicle floor) and longitudinal stop accuracy. The performance of precision docking is subject to legal performance requirements from the Americans with Disability Act (ADA)[4]. In general, the horizontal gap between docking station and vehicle floor, measured when the vehicle is at rest, shall be no greater than 7.62 cm (3 in). The vertical gap between vehicle floor and station floor shall be within plus and minus 1.58 cm (5/8 in). Although there is no specific requirement for longitudinal stopping position accuracy in ADA, the docking demo experiences in Washington DC and San Diego suggest that 10-30 cm longitudinal stopping accuracy requirement will be adequate.

4.1.1.1.2 Transition characteristics

a) Driver initiation and restriction: The driver can initiate the transition between manual and auto modes. However, if vehicle locations are within 0.1 m laterally and 3 m

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[4] http://www.usdoj.gov/crt/ada/reg3a.html.

longitudinally of the platform, the driver can only select the stopping of the vehicle but manual steering cannot be selected, in order to avoid possible impacts with platforms.

b) Transition time: The transition from manual to auto modes takes no greater than 0.5-1 seconds and the transition from auto to manual takes no greater than 0.15 seconds.

4.2.1.2 Lane keeping performance

4.2.1.2.1 Accuracy

The lane keeping accuracy requirement is determined by the lane width and vehicle geometry. For example, if a lane keeping function is required for an 8.5 ft wide (e.g., a New Flyer 40 ft bus) bus riding on a 10 ft narrow lane, the maximum allowable deviation from the lane center is 0.75 ft. (22.8 cm). The lateral tracking error with respect to lane center should be kept within 50 to 60 percent of the maximum allowable deviation (0.375 ft to 0.45 ft) for the whole speed operating range.

4.2.1.2.2 Operating conditions - All weather conditions, with transition initiated by drivers

4.2.1.2.3 Transition characteristics

a) Driver initiation and restriction: The driver can initiate the transition between manual and auto modes when the system is ready. The system should be ready during most normal driving time.
b) Transition time: The transition from manual to auto modes takes no greater than 0.5-1 seconds, and the transition from auto to manual takes no greater than 0.15 seconds.

4.2.2 Safety

System safety for safety-critical systems is measured using the Mean Time Between Hazards (MTBH), while the hazards are classified into four levels: catastrophic, critical, marginal, and trivial. Typically, MTBH is specified for each level of hazards. MTBH is used for transit rail systems (e.g., 10^{-7}-10^{-9} MTBH is used for catastrophic hazards). However, there have been no comparable safety measures currently used by the bus transit industry. Definition of safety requirements and evaluation of system safety levels are complicated. Under this study, as reported in Section 4.4, this research team began the initial investigation of both of these issues,

It is important to note that the driver can, by design, become an integral portion of the system when hand-over or transition of vehicle control from computer to manual operation is made in either fail-safe (capable of compensating automatically and safely for a failure) or fail-soft (capable of operating at a reduced level of efficiency after the failure of a component or power source) manner. A critical part of this handover is insuring that the driver is prepared to take control of the vehicle. It may be necessary to first alert the driver of the failure and require some positive response on his/her part before handing over control. If this response is not immediately forthcoming, the bus should automatically be brought to a stop. To adequately prepare for and respond to emergencies, a scenario-based system should be developed and used, together with a fault tree analysis to develop ways and means that the system will respond to various situations.

4.2.3 Reliability

System reliability is customarily measured in terms of the Mean Time Between Failures (MTBF) of infrastructure and onboard systems, subsystems, and components under the intended operating conditions and environments (such as weather conditions). Because electronic guidance systems are relatively new and can be implemented using a number of different technologies, there is no universally accepted standard. Each transit agency must develop its own guidelines based on current maintenance procedures, willingness to pay, and planned application. While it may be technically possible to build a system that is virtually failure free, after a certain point, the marginal cost for each additional “unit” of reliability becomes prohibitive.

System reliability is tied closely with component reliability and often tied together with an agency’s choice of technologies. The magnetic markers embedded in the road for magnetic guidance, for example, have no parts that can fail and are virtually impervious to weather, but GPS and vision systems can be subject to signal interference.

System reliability can also be greatly affected by infrastructure designs. An example of the planned application’s influence on setting reliability requirements is a segregated route utilizing a single lane for both directions of travel, which would require a higher level of reliability since a failure that disabled a bus would block the entire system. Conversely, in a dedicated (but not segregated) bus lane, short headways would allow a bus to be taken out of service (and moved to the side of the road) with little effect on system performance, thus allowing for less demanding reliability standards.

4.2.4 Availability

Availability incorporates not only the reliability of the system (the probability that it will not suffer a failure), but also the time required to restore it to full operation. Availability is closely tied to system design, quality of routine maintenance, and system reliability. Transit agencies need to specify this measure based on the characteristics of their fleet size, operation and maintenance policies, etc.

System design should allow for ease of checking and calibrating so that problems can be found before they become failures. One possibility for routine testing would be a short test track in the maintenance yard so that each bus’ guidance system could be checked as the bus left the yard to begin its daily run.

Design again comes into play in the event of a failure in the field. It should be simple and fast to find and replace the faulty module so that the bus can quickly be placed back in service. The ease and speed of repair, combined with the quality of routine maintenance, will determine the number of buses that need to be kept in reserve in order to maintain the desired level of service.

Infrastructure availability must also be taken into consideration, including adverse weather conditions, e.g., snow or ice in the busway or possible effect of a crash on the adjacent traffic lanes. In the event of a guidance system failure, either on-board or with the infrastructure, that cannot be repaired, the system should be designed so that the bus can operate manually, albeit at reduced speed.

4.2.5 Maintainability

The electronic guidance system should be at least as durable as other onboard systems so that the current service cycle can be maintained. Suppliers of the systems should be required to modularize their systems for ease of replacement, seal them sufficiently to withstand road hazards and bus cleaning, and equip them with a high level of self diagnostic capabilities. The emphasis should be on a system designed with more modules rather than fewer. In this way replacement of a module that is beyond repair will be cheaper, pulling and replacing by the maintenance staff will be easier, and spare modules will be more like commodity items than specialty items.

As buses have become more complex, the trend is to outsource more and more of the repair work, even in such “traditional” areas as engines and transmissions. The transit agency must decide which guidance system repairs will be carried out in-house and which will be sent out although the modular “black box” nature of the guidance system will favor the latter.

The introduction of any form of electronic guidance technology will have an effect on the maintenance division of the transit agency involved. While this is inevitable, it need not be onerous, and in fact, part of the choice of technology should be directed at minimizing this effect. A well designed system should not require <u>significant</u> changes in procedures, additional expertise, or expense for preventive maintenance, diagnosis of system problems, infrastructure (e.g., lane markings), or system calibration. Among the areas potentially requiring some modification of current maintenance practices are:

A. **Infrastructure maintenance**: Each electronic guidance technology uses distinct infrastructure features, which have different reliabilities, life cycles, and levels of required maintenance. As the infrastructure features for electronic guidance are likely installed for that sole purpose, maintenance responsibilities are likely to fall to the transit agency that operates the system. Lane lines for vision-based systems, for example, will require periodic re-striping in order to maintain legibility. A wire guidance system would require regular inspection and maintenance of the roadway power and receiving units.

B. **Calibration**: The sensors are the ‘eyes’ of the lane system, and need to be calibrated in relation to the infrastructure reference. Steering actuators may also need calibration in order to ensure that the steering angle commands are implemented correctly. Because the sensors are vital to the overall system performance, calibration of these devices is critical. There are several stages of calibration: at the initial system installation, after the sensors are repaired or replaced, and when periodic inspections are conducted. Although an automated calibration process can be developed, involvement of maintenance staff will be needed in order to ensure the calibration is done correctly.

C. **Regular inspection:** Because of the safety critical nature of the electronic guidance system, overall system inspection needs to be performed at predetermined time intervals throughout the life of the system. It is likely that suppliers of the electronic guidance technologies will modularize their systems and provide diagnostic tools for routine inspections. However, inspections will have to be conducted by maintenance engineers or technicians who will need to have an understanding of the technology and the system.

D. **Repair:** Like any other system or device, system failures or faults are inevitable and repairs will be needed. System designs will, to various degrees, allow a malfunctioning module to be quickly and easily pulled and replaced. Repairs will need to be performed by maintenance engineers or technicians whose understanding of the technology and system will greatly affect its performance and safety. As these repairs may exceed current staff capabilities, it must be decided whether it would be better (and in the long run, cheaper) to train in-house staff or contract out the repairs.

4.2.6 Compatibility with Existing Infrastructure

If the BRT system will be using a dedicated bus lane or operating in a mixed traffic environment, there is the very real possibility that motorists will become confused as to when they are and when they are not allowed into the bus lane. There will be times, such as at intersections, when they will be required to cross the lane either to simply get across the intersection or to make a turn. Therefore, requiring that they remain clear of the lanes at all times is not feasible. Striping or different colored roadways (or different surface materials) will work between intersections or highway exits, but that still does not completely solve the problem at intersections.

4.3 Preliminary Technical Specifications

According to the system performance requirements, the subsystem (e.g. sensors and actuators etc) requirements for electronic guidance can be determined.

4.3.1 Vehicle position sensing capability

Determining the vehicle's lateral deviation to lane center with high accuracy, high bandwidth and robustness is very important to the successful implementation of electronic guidance/assist systems. Measurement of the vehicle location may be achieved by one individual sensor or a combination of multiple sensors on the bus, or be received from other sensors outside the bus through communications.

4.3.1.1 Spatial Coverage

Generally, spatial coverage should cover the whole width of the desired operating roadway. The spatial coverage requirement can be smaller under certain operation scenarios.

4.3.1.2 Resolution

The position sensing resolution should be better than ¼ of the positioning accuracy requirements. For example, in the case of precision docking, the position sensor resolution should be around 1-2 cm.

4.3.1.3 Robustness with respect to environmental changes

The measurements of the vehicle position sensing system should be consistent regardless of changes in environmental factors. For example, it should work similarly for road surfaces with/without snow and ice, rural roads with clear view of the sky and urban environments with partially or totally blocked sky, and clear view of road or foggy weather with low visibility.

4.3.1.4 Timing and update rate

a) Delay: The sensing time delay requirement depends on the maximum operating speed. If the maximum operating speed is 60 mph (e.g. for lane keeping), the sensing delay from input to output should be shorter than 0.1 s.

b) Update Rate: The requirement is similar to the time delay requirement. If the maximum operating speed is 60 mph (e.g. for lane keeping), the sensor data update rate should be at least 10 Hz.

4.3.2 Subject vehicle status sensing capability

Transit bus lane-assist systems may employ subject vehicle sensors to obtain the status of the subject bus, the bus driver’s operations, and probably also the bus driver’s status, e.g., attentiveness, fatigue, etc. The following items specify the requirements for the subject vehicle sensors.

4.3.2.1 Vehicle status parameters

a) Speed: The maximum bus speed that the sensor can measure should be at least 10 mph above the system maximum operating speed. The minimum bus speed that the sensor can measure should be no greater than 1.8 mph (0.8 m/s).

b) Yaw rate: The maximum yaw rate that the sensor can measure should be at least 150 deg/sec while the minimum should be no greater than 0.25 deg/sec. The resolution of the yaw rate sensor should be better than 0.001 deg/sec.

c) Steering wheel angle: The steering wheel angle sensor should be able to measure the absolute position of the steering wheel. The sensing range should be as wide as the maximum range (750 degrees for 40 ft New Flyer bus) of the steering system, with 1 degree accuracy.

d) Brake pressure: The brake sensor should be able to measure the full range of brake pressure (i.e., 0-120 psi for 40 ft New Flyer bus) with a resolution of about 1 psi.

e) Data Bus communication: Since an on-board J-bus or data network has become a primary trend for transit vehicles, it will be advantageous for lane-assist systems to be equipped with capabilities to read and send data from the J-bus.

f) Inertial navigation system (INS): As a necessary backup for vehicle location sensing, it would be advantageous to equip the vehicle with INS so that dead reckoning could be executed to estimate the location of the vehicle between sensing samples or when other sensing functions are temporarily lost.

4.3.2.2 Events

All events, such as door open/close, light on/off, etc., that indicate conditions that are relevant to lane-assist applications, should be converted into signals readable by on-board computers or transferable from the data bus.

4.3.3 Actuation

4.3.3.1 Steering actuator

The steering actuator receives steering commands and turns the steering wheel to the desired angle according to these commands. It is the most important actuator for lane keeping and precision docking.

Functional requirements: The steering actuator functional requirements for lane keeping and precision docking operations are listed as follows.

a) Position servo: The function of the position servo is to take the steering commands issued by the upper level controller and turn the steering wheel to the desired steering wheel angle.

b) Smooth transition between manual and automatic mode: To enable transition between the driver and automatic driving, the steering actuator should have a transition function between manual and automatic modes.

c) Self-calibration of zero steering angle: Steering actuator should be able to calibrate the steering angle sensor and find the zero steering angle when the system starts.

d) Fault detection and self diagnosis

e) Torque mode if haptic feedback is needed for DVI purpose

f) Position servo performance: The position servo should at least achieve 1 degree accuracy (steering wheel angle) with 4-5 Hz bandwidth.

g) Rated torque for steering actuator: The actuation force of the steering actuator can be generated electronically (by a motor) or hydraulically. The power of the steering actuator should be large enough to overcome friction torque from vehicle tires, especially during low speed situations such as precision docking. It is desirable that the power of the steering actuator be low enough so that the driver could overcome it in the event of an emergency.

h) Nonlinearities associated with steering mechanism: The original bus steering mechanism has various nonlinearities which may increase the difficulty of control system design for precision docking and lane keeping functions. For example, the free play should be limited to no more than 20 degrees (steering wheel angle).

4.3.3.2 Engine and brake actuator

If speed control is required for lane keeping and longitudinal automatic stop is required for precision docking, engine and brake actuators will be needed to control bus longitudinal motion. Different bus engine (e.g. CNG or diesel), transmission, and brake systems configurations have different requirements for engine (throttle for spark ignition, fueling for diesel) and brake actuators.

4.3.4 Driver-Vehicle Interface system

4.3.4.1 Interface Contents

a) Vehicle to Driver: System-relayed vehicle conditions, system critical faults, and system response to driver action or request. The system also should provide feedback that a request has been received from a driver so that the driver knows that a request is being processed. When the system requires an action from the driver, the system should provide some preview information to the driver, such as through sounding a tone.

b) Driver to Vehicle: Means of making request or selecting functions, and channels for activation if essential for system.

4.3.4.2 Processing capability

a) Delay: The processing delay from processing computer to interface unit should be shorter than 0.1 s, and from interface unit to processing computer should be shorter than 0.1 s

b) Data processing rate: The system processing batch rate should be at least 5 Hz.

4.3.4.3 Display update time

The DVI should have an update time of no greater than 200 ms.

4.3.5 Infrastructure requirements

The required modifications of infrastructure to adopt electronic guidance systems depend on the type of operational venues, selected technology, and the desired level of service features. Some examples of influences on infrastructure needs are listed below:

A) Operation Scenarios or Applications:
  - Newly created bus lanes in median: This will require the construction of added lanes and dividers to utilize the median as dedicated bus lanes.
  - New division of existing roadways into special bus lanes: This may involve the re-striping of existing lanes into narrower paths or the creation of a shoulder lane.
  - Narrow bridge or toll booth: This will require minimum modifications on the bridge or at toll booths. However, there may be a need for changes of road markings or magnet installation to accommodate the lane guidance system for buses to pass through with electronic guidance functions.
  - Dedicated busways: To protect high-speed bus operation from other traffic on HOV lanes, corridors or special bus ways, some dividers or barriers may be needed.

B) Technology Selection
  - Vision-based control: This approach uses cameras to capture images of the roadway as the basis for vehicle guidance and control. Therefore, the striping or lane markings must be made conspicuous to the cameras.
  - Magnet-based guidance: This involves the installation of magnets in the pavement, typically at intervals of 1 meter or more.
  - Other technical approaches: Please see the Technology Options section for more descriptions.

C) Desired Services
   - Precision docking: To allow precision docking, stations or bus stops may need to be altered to allow the vehicles to dock closely to the platform, thus truly passenger-friendly, expedient alighting and boarding can be realized.
   - Coordinated multiple-bus maneuvers: In a fully-expanded BRT operation, the system must allow vehicles to join or split from a sequence of buses or a convoy of vehicles. Therefore, there will be a need for converging or diverging roadway designs along the bus way, which may also require the implementation of vehicle-to-vehicle and vehicle-to-roadside communication as well as infrastructure modifications to minimize crossing patterns with other traffic in safety-critical junctures.

4.3.5.1 Roadway sensing and construction

a) Reference marking installation: The installation requirements for infrastructure marking depend on the type of technologies used. For example, the magnetic marker should be buried at a certain depth (variation should be kept within 0.5-1 in) and perpendicular to the road surface.

b) Roadway and transit stop construction: Significant benefits can be derived from savings on infrastructure construction. For example, narrow lanes can reduce the required use of land as well as pavement costs. There are preferred ways of constructing bus platforms and curved sections of roadways. The requirements are site dependent and need to be planned in the deployment phase.

4.3.5.2 Communication capability

BRT services rely on vehicle-to-roadway or vehicle-to-vehicle or infrastructure-based communication to provide effective and enhanced performance. Since lane assist is an integral part of BRT, planning is necessary to implement application-related communication links.

4.3.6 Driver qualification and training requirements

4.3.6.1 Qualification

a) Transit vehicle experience: At least 2 years of transit vehicle driving experience

b) Training and evaluation tests: Initial and follow-up training courses with evaluation tests

4.3.6.2 Training

a) System training: Overall lane-assist application, system operation, and fault management issues

b) DVI training: System response, driver interaction, emergency handling

4.3.7 Maintenance interval minimum requirements

a) Mileage -- Every 6,000 miles.
b) Time interval -- Every 1 month.
c) Routine diagnostics --Daily, weekly and monthly test procedures.

At the present time the service life of a bus is approximately 20 years. Given the current pace of changing technology, is it a reasonable expectation that the transit agency will want to continue with current guidance technology for the life of the bus? If the answer is yes, will replacement parts be available 10 or 15 years from now? While the overall guidance system may be state-of-the-art, it should be constructed with proven, off the shelf components that can reasonably be expected to be around for a long time. Also, there should be assurance that future upgrades will be backwards compatible so that the entire system will not have to be replaced.

4.4 Measures of Effectiveness for Evaluating Lane Assist Systems

In order to determine how well a lane assist system meets the needs of the customers, it is necessary to have measures of effectiveness that capture the most important system attributes. The measures of effectiveness for lane assist systems will include some that can be quantified and others that cannot (and must therefore remain qualitative). The quantitative measures are likely to be most useful for making investment decisions and choosing among alternatives, but the qualitative measures cannot be ignored because they could become “make or break” factors.

Furthermore, the definition of the baseline cases for comparison with the lane assist cases will in some cases be challenging, because there may not be a direct “before and after” case to compare, with the only difference being the lane assist system, or it may be necessary to compare with typical situations in other “comparable” locations rather than in the same location. If the implementation of lane assist technology is combined with other changes (new busway infrastructure, new branding of bus service, etc.), care will be needed in separating out the individual effects of these changes.

Candidate measures of effectiveness to use for evaluation of lane assist systems are:

4.4.1 Incremental costs to provide lane-assist capabilities

In each of these cases, care is needed to focus on the costs (both positive and negative) specifically attributable to the lane assist system rather than other investments being made at the same time. In each case, the units will be dollars, and all should be projected to a common baseline year (typically, the year the decision is made to proceed).

- 1.1 Cost per bus of adding lane assist capability
  - 1.1.1 Capital cost
  - 1.1.2 Annual maintenance cost

- 1.2 Cost per mile of adding guidance capability to busway
  - 1.2.1 Capital cost (note that this could be a negative cost if it represents a saving in the cost of constructing a busway attributable to reduced lane width)
  - 1.2.2 Annual maintenance cost

- 1.3 Cost per bus station of adding precision docking capability
  - 1.3.1 Capital cost
  - 1.3.2 Annual maintenance cost

- 1.4 Deployment start-up costs for training bus drivers and maintenance personnel

4.4.2 Operational improvements

The primary benefits of lane assist systems should be found in this category, and to the extent possible the MOEs defined here should be amenable to conversion into monetary values.

4.4.2.1 Travel Time Saving

> Travel (running) time saved by using lane assist, compared to manual steering on the same width lane. This should represent the reduction in travel time associated with the ability to run at higher speed in lanes of restricted width. It could be expressed in terms of a percentage time saving for the bus route as a whole or an absolute value of time saved (in minutes or seconds). The monetary value of this time saving can be estimated in three different ways: (a) multiplied by agency's average cost per hour of bus operation; (b) combining (a) with the value of time saved by all the passengers using the bus; (c) estimating the potential cost avoidance if the time saving is sufficient to reduce the number of buses and drivers needed to provide the intended level of transit service.

4.4.2.2 Time Savings at Bus Station

Time saved per bus stop using precision docking (combination of time saved in approach and in passenger boarding and alighting), compared to less accurate manual approach to same bus stops. This should be expressed in terms of seconds per bus stop. The monetary value of this time saving can be estimated in three different ways: (a) multiplied by agency's average cost per hour of bus operation; (b) combining (a) with the value of time saved by all the passengers using the bus; (c) estimating the potential cost avoidance if the time saving is sufficient to reduce the number of buses and drivers needed to provide the intended level of transit service.

4.4.2.3 Time Savings for Passenger Boarding and Alighting

Time saved per passenger boarding and alighting with precision docking, compared to less accurate manual approach to same bus stops. This would be an important component in estimating 2.2 above.

4.4.2.4 Passenger Ride Quality

Improvements in passenger ride quality (measured in r.m.s. lateral acceleration during steady cruising, peak lateral acceleration in transients, and r.m.s. lateral jerk), compared to driving the same route with a representative sampling of normal bus drivers. This cannot be converted into a direct financial benefit, but has a more subtle effect on passenger perception of the transit service quality.

4.4.2.5 Operating Speed

Maximum operating speed (mph), and lane tracking accuracy at that speed (r.m.s. lateral error for steady cruising and peak lateral error for a specified road geometry change transient, measured in cm). These are intermediate measures, which can become components of 4.2.3.1 and 4.3.2.2.

4.4.2.6 Lateral Position Accuracy

Lateral position accuracy of precision docking (cm). This is a direct physical measure that contributes to 4.3.2.2.

4.4.3 Safety

Safety is another decisive MOE that cannot be translated directly into financial terms. However, it is fair to assume that a lane assist system cannot be judged any less safe than the normal bus driver steering process that it supersedes. Hence, the relevant MOEs should be defined in terms of the change in frequency of occurrence of several types of incidents, with and without lane assist in use. This could be evaluated per mile or per hour of bus operation for incidents of the following classes:

- Property-damage-only crashes
- Injury crashes
- Fatality crashes
- Abrupt maneuvers causing passenger falls
- Boarding/alighting injuries and fatalities
- Incidents involving injuries to pedestrians other than passengers

Safety of a newly designed system can be determined through thorough safety analysis. Methods for safety analysis are discussed in Section 4.4.

4.4.4 System Reliability and Availability

These are technical MOEs that do not translate directly into financial terms. However, they could be decisive in determining whether a system is viable. If the reliability or availability is below minimum acceptable thresholds (which could vary by agency), the lane assist system could be judged a failure regardless of any of its other merits.

4.4.4.1 Mean time between failures (MTBF)

MTBF is measured in vehicle hours, for failures of several different severity levels. The more severe the failure, the longer the MTBF needs to be. This will be difficult to determine for any new system before it has accumulated substantial operational experience.

4.4.4.2 Availability

System availability is the percentage of time when the system should work that it actually does work. This is defined as a numerical fraction or percentage, and should typically be a decimal point followed by multiple 9s.

4.4.5 Maintenance Burden

Although not necessarily a decisive factor, transit properties will be reluctant to support a system that significantly increases their maintenance burden. The maintenance needs of the lane assist system do not need to be zero, but they at least need to be consistent with the maintenance requirements for other major bus subsystems so that all can be maintained on similar schedules. The relevant MOEs appear to be:

- Frequency of preventive maintenance needed by lane assist systems
- Additional staffing, facilities or equipment needed to maintain lane assist systems.

4.4.6 Operational Limitations

The lane assist system should not generally impose restrictions on the operating capabilities of the transit property, and should be able to operate under all weather conditions in which the buses can be operated by their normal drivers. The public relations implications would be very negative for a new system that is less capable than the “old” system. The relevant MOEs to ensure no adverse weather limitations appear to be:

- Maximum permissible rate of rainfall (inches per hour)
- Maximum permissible rate of snowfall (inches per hour)
- Minimum permissible visibility (feet)
- Maximum permissible accumulation of snow on running surface (inches)
- Maximum permissible wind speed (miles per hour).

4.4.7 Infrastructure Effects

Some of the most dramatic potential impacts of lane assistance are on the infrastructure requirements for busway operations. If the accurate and consistent lane keeping of the lane assist system can reduce infrastructure width, the potential benefits could be extremely large, especially in the most congested and space-constrained locations. The relevant MOEs appear to be:

- Minimum allowable lane width for straight track (feet or meters)

- Minimum allowable lane width for curves of several radii. Note that unless a bus has all-wheel steering, it is physically impossible for the rear wheels to follow exactly the same track as the front wheels on curves. Simple geometric calculations shown in Appendix A demonstrate the ideal case of additional width needed as a function of bus wheelbase and curve radius.

- For specific deployments, translate these into total infrastructure ROW and construction cost savings compared to use of standard lane width (dollars).

4.4.8 Public Perception

Public perception is a notoriously subjective concept and not amenable to well-defined quantitative MOEs. It may be possible to gain a sense of the public perception of the safety and quality of service of a new bus system by doing surveys before and after the introduction of the new system. Changes in ridership could also represent a quantitative measure of the net reaction of the public to the new system.

4.4.9 Driver Acceptance

Driver reactions are likely to be similarly subjective to the public reactions, and can also be colored by other issues arising at about the same time as the advent of a lane assist system (disputes over other issues, new contract negotiations, changes in work rules, etc.). Driver attitudes toward the lane assist system could be surveyed, either formally or informally. Particularly negative reactions to the system could be detected in the event that many complaints are registered or the systems are found to be sabotaged.

4.5 SAFETY ANALYSIS

Preliminary hazard analysis is the first step of safety evaluation. The methodologies for determining the safety integrity levels for safety-critical systems are covered in Section 4.4.1. Preliminary hazard analysis of Lane Assist Systems is given in Section 4.4.2.

4.5.1 Determination of Safety Integrity Level

The design of safety-critical systems involves a certain amount of work in conformance with the safety program to define the critical components. The primary work is related to identifying and determining the critical components. The determination of integrity level influences the development approaches and the assessment level to be performed on the process and the product itself. The safety integrity levels are allocated by identification and analysis of hazards, as well as by assessment and classification of risks.

The hazard identification and analysis aims to cover all system safety behavior by taking into account its environmental conditions. This activity starts by identifying the system and safety boundaries, then performing a preliminary hazard analysis to identify the actual and potential hazards perceived within these limits. This analysis allocates to each hazard or group of hazards a severity category. Four categories of hazard severity are classified, in qualitative terms, depending on the consequences of the system's reaction to failure. The four classes of hazards are catastrophic, critical, marginal, and trivial, as depicted in Figure 4.3.

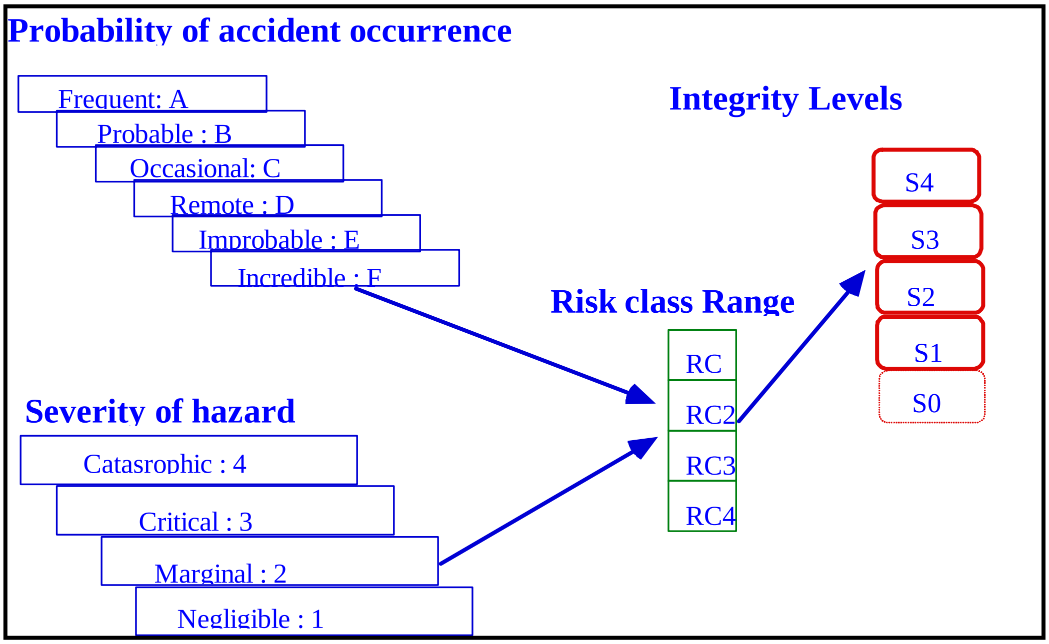

Figure 4.3 Safety Integrity Level (SIL) Determination

4.5.2 Preliminary Hazard Analysis of Lane Assist Systems

In this section, we'll identify hazards associated with each of the safety functions. Certain elements or phenomena of hazards are similar in different system functions, while others are unique to individual cases. Associated with each system function, there is a list of components and related failures that may result in those hazards. A table of components is developed for all targeted systems to show the linkage between component failures and external events that are related to hazards.

The system functions of automatic electronic guidance are identified first:

Automated lateral control (lane following, lane change, docking)
Automated longitudinal control (speed control, engine and brake control)

We will examine the lane following functions and the speed control functions.

4.5.2.1 Categories of Hazards in Lane Assist Systems

To analyze the criticality of hazards, the types of hazards must be identified first. Certain hazards are similar in systems with different technologies, while others are distinct in their nature. Generally speaking, there are five major categories of hazards for Lane Assist systems: environment, driver, equipment, passenger, and design-related. They are detailed further below.

Environmental factors – such as weather or infrastructure problems.
Environmental hazards most influential to lane assist systems are fog, rain, and ice conditions. Infrastructure related problems include EM interference on sensors (GPS, magnets), road roughness, and obstacles on the roadway. The direct effects on lane assist operations are:

- Performance of sensing devices deteriorates in these conditions,
- Uncertainty of vehicle control increases due to changes in vehicle-roadway interface
- External disturbance causes the vehicle to deviate from its course.

Driver actions – driver alertness or readiness or intervention.
Driver actions or inactions can become causes of crashes. Drivers may fail to take actions due to drowsiness, unconsciousness, or inattention. They may react improperly due to distraction, panicking, or wrong perception and misunderstanding. The last two items may be consequences of insufficient training or poor design of human-machine interface.

Component or function failures.
Equipment and functional failures can certainly lead to hazardous conditions. The types and causes of these failures will be discussed later with a functional decomposition of the candidate lane assist systems.

Passenger actions – behaviors, responses, or conditions that may affect operations.
Passenger actions are a concern in transit systems. Due to the interaction between drivers and passengers, the actions of passengers may propagate into driver response that leads to crashes. For the purpose of discussion, we will neglect this category for now but group related concerns into those in the driver category.

Design errors
Safety hazards can be created by specification or design errors. Specification errors and design errors may not be present as a hazard until one or more of the above described failures or errors occur.

4.5.2.2 Hazard Analysis for Lane Assist and Precision Docking Systems

4.5.2.2.1 Hazard Identification

Common hazards H(..) for lane assist and precision docking systems are:

Environmental-related:

a) Loss or deterioration of lateral positioning accuracy due to infrastructure: Example of such hazard include GPS guidance antenna losing the ‘lock’ with required number of satellites, or a magnetic marker system interfered with by background noise.
b) Loss or deterioration of lateral positioning accuracy due to weather conditions: This may arise, for example, from a computer-vision system in a foggy situation.

c) Loss or deterioration of tire control due to weather conditions: This can be caused by slippery or icy road surfaces.
d) Intrusion of surrounding vehicles or unavoidable traffic hazards (system limitations): The movement of other vehicles may intrude into the path of the subject vehicle and result in a hazardous situation while the subject vehicle is functioning properly within its design requirements.

Driver-related:
e) Driver non-alert or inattentive: This refers to the situation when the driver fails to take a necessary action, even if it is properly indicated by the system.
f) Driver taking inappropriate action: This situation can occur for two main reasons; if the driver takes the wrong action due to a false understanding of how the system works or if the driver takes an appropriate action but mistakenly uses the wrong control or wrong sequence of controls.

Equipment-related:
g) No control: This hazard occurs when the system does not generate a control command when it is warranted.
h) Control ineffective: This condition is caused by deficiencies of actuators.
i) Faulty control command due to erroneous signal processing or DVI errors: The control signal is incorrectly generated when it is unwarranted.
j) Lateral positioning sensing errors due to sensor failure.
k) Vehicle state sensors information incorrect.
l) Computer hardware failure.
m) Computer software failure.
n) Communication network failure.

A combination of the hazards may result in collisions with other vehicles or obstacles or may cause unnecessary maneuvers, which lead to subsequent hazards to neighboring vehicles.

4.5 .2.2.2 Relationship Between Failures and Hazards

Hazards often can be associated with the failure of functional blocks. The following table shows the cause and effect relationship among the hazards H(a) through H(n) and the failures of functional blocks S(i) through S(v). A cross mark in a table cell indicates that the sub-system is a potential contributing factor to the hazard.

Table 4.1 Relationship Between Failures And Hazards

	S(i)	S(ii)	S(iii)	S(iii)	S(iv)	S(v)
H(a)						
H(b)						
H(c)						
H(d)						
H(e)					X	
H(f)					X	
H(g)	X	X		X		X
H(h)			X			
H(i)		X		X		
H(j)	X					
H(k)		X				
H(l)		X				
H(m)		X				
H(n)		X				X

4.5.2.3 Failure Mode Effect and Criticality Analysis

Failure mode analysis has to be applied to a well-defined system with clearly defined inputs and intended outputs. The definition of the system is done by the functional decomposition and analysis. An example of the failure mode analysis for an exemplar vehicle electronic guidance system is given in Table 4.2 below.

Table 4.2 FMECA for Lane Assist and Precision Docking System

Function	Output	Failure	Effects	Hazard	Necessary condition	Severity	Dangerous Situation
Sensing							
lateral position	position relative to lane center/ markings	initial no lateral position detection	can not engage auto steering	side collision	transfer control in motion/ driver release control/ vehicles in adjacent lane	Critical	no detection of lateral position
				manual control	transfer control in motion/ driver re-gain control	Negligible	no detection of lateral position
		loss lateral position detection	cause unwanted deviation	side collision	deviation with large yaw rate	critical	no detection of lateral position
			cause unwanted deviation	side collision	deviation with minor yaw rate	Moderate	no detection of lateral position
		under-measuring	smaller steering correction than needed	side collision	no means to stop the vehicle before collision	Critical	error measurements
			smaller steering correction than needed	jerky motion	driver take over/ stop	negligible	error measurements
		over-measuring	greater steering correction than needed	side collision	no means to stop the vehicle before collision	critical	error measurements
			greater steering correction than needed	jerky motion	driver take over/ stop	negligible	error measurements
Yaw angle	angle between vehicle longitudinal axis and road center line	lose yaw angle measurements	induce unwanted steering	side collision	control heavily relies on yaw angle	critical	no yaw detection
			induce jerky motion	unstable control	yaw angle as supplementary inputs	negligible	no yaw detection
Yaw rate	change of yaw angle as a function	lose yaw rate measurement	induces unwanted steering	side collision	control heavily relies on yaw rate	critical	no yaw rate detection

	of time						
			induces jerky motion	unstable control	yaw rate as supplementary inputs	negligible	no yaw rate detection
lateral acceleration	change of lateral deviation	lose acceleration measurement	induces jerky motion	unstable control		negligible	no acceleration
steering angle	steering angle measurement	no steering measurement	large steering action	side collision	no backup available	critical	no steering angle measurement
		steering measurement greater than actual	smaller steering action than needed	unstable control		moderate	steering angle measurement greater than actual
		steering measurement smaller than actual	large steering action	side collision	road curves	critical	steering angle measurement smaller than actual
				side collision	no backup control or braking available	moderate	steering angle measurement smaller than actual
road geometry	upcoming road geometry	no/incorrect upcoming road geometry	larger deviation	no			
vehicle speed	velocity of vehicle	no velocity	no steering command	vehicle drift	no error speed detection / road turns	critical	no speed
		speed greater than actual	incorrect steering command	unstable control	no backup actions	critical/moderate	speed greater than actual
		speed smaller than actual	incorrect steering command	unstable control	no backup actions	critical/moderate	speed smaller than actual
Processing							
vehicle status	a combination of vehicle lateral position, yaw motion, and other observable parameters	in accurate observation of vehicle status	incorrect control command	side collision	when control command is larger than needed	critical	inaccurate vehicle status processing
steering	steering angle	no command	no steering	side collision	road turns	critical	no steering command

control command	command		correction				
		provide larger steering command than desired	large steering correction	side collision	rapid motion and no backup can react	critical	no steering command
			larger steering correction	side collision	backup reduces the lateral acceleration prior to entering adjacent lane	moderate	larger steering command
			larger steering correction	side collision	backup prevent vehicle entering adjacent lane	negligible	larger steering command
		provide smaller steering command than desired	smaller steering correction	side collision	road curves	critical	smaller steering command
				side collision	no backup control or braking available	moderate	smaller steering command under-steer
Actuation							
steering actuation	steering angle change	no steering action	vehicle drift from lane center	side collision	road curves	critical	no actuation
			vehicle drift from lane center	side collision	no backup control or braking available	moderate	no actuation
		under-steer	induce larger deviation	side collision	road curves	critical	under-steer
			induce larger deviation	side collision	no backup control or braking available	moderate	under-steer
		over-steer	provide larger steering action than needed	side collision	rapid motion and no backup can react	critical	oversteer
			provide larger steering action than needed	side collision	backup reduces the lateral acceleration prior to entering adjacent lane	moderate	oversteer
			provide larger steering action than needed	side collision	backup prevent vehicle entering adjacent lane	negligible	oversteer

4.6 Summary

In developing the electronic guidance system requirements and specifications, we started with a functional analysis of lane assist and precision docking to identify a functional architecture that defines the elemental functions required to implement lane assist and precision docking and the input-output relationships among the functions.

The results are translated into system functional requirements in as quantitative a manner as practical. Subsequently, technical specifications are defined based on the decomposed elemental functions for lane assist and precision docking under the intended operational conditions/environments and internal and external constraints.

In order to assist transit properties/implementers to select the most effective approaches and technologies for their applications, the project team also developed a set of qualitative (and quantitative whenever possible) Measures of Effectiveness (MOEs) and conducted a preliminary study of safety analysis methods.

5.0 Conclusion

This is the final report for the project "Development of Needs and Requirements for Transit Lane Assist Systems", sponsored by the Federal Transit Administration and California Department of Transportation and conducted by AC Transit, Los Angeles County Metropolitan Transportation Authority (LACMTA), Lane County Transit District (LTD), and San Diego Association of Governments (SANDAG), the California Department of Transportation (Caltrans), Gillig Corporation and California PATH Program (PATH). The project achieved its original goals to identify transit needs for lane assist and precision docking systems and to define both performance requirements and technical specifications for these systems.

The project team conducted case studies of the BRT systems being developed by four partner agencies. The case studies of the BRT sites have addressed the following issues:

- Needs, functionalities, and applications of lane assist systems
- Cost/benefit analysis of lane assist systems and their benefits (and potentially combined benefits with other advanced technologies)
- Drivers' perspectives on lane assist systems
- Operational environment and conditions including constraints
- Maintenance aspects of lane assist systems

The workshops with representatives from the four transit agencies, combined with studies of the background information about their BRT system plans, provided a rich set of information for the development of the needs and the requirements for lane assist and precision docking systems. Through workshops and close interactions, the inputs from the transit agencies were synthesized to capture the common and special needs, benefits and constraints of each type of application for the lane assist and precision docking systems. The synthesized findings, reported in Chapter Two of this report, showed that all of the partner transit properties are interested in implementing some forms of lane assist and precision docking systems for BRT applications.

Based on the stakeholders' inputs, the project team conducted in-depth studies on needs, benefits and costs and deployment issues for lane assist and precision docking systems. This study, summarized in Chapter 3, revealed that lane assist and precision docking systems offer significant benefits over traditional buses. In addition to the capability of operating buses within narrow lanes, which offers the most dramatic and quantifiable benefits for enabling higher quality and lower cost BRT systems, lane assist also offers a significant number of subtle and less readily quantifiable advantages, including higher operation reliability, improved mobility and ride quality for passengers, reduced stress for drivers and enhanced image for the transit agency. The economic evaluation revealed that the precision docking functions offers large benefit/cost ratios with even small amounts of time saved at each bus stop. The lane assist system can offer even greater benefits from the reduction of the cost of the roadway construction due to narrow lane width. The safety analysis, based on extensive collision data for both transit buses and light rail, suggested that should BRT buses operate in a similar manner as light rail trains, many incident types common with traditional bus transit, such as side collisions and passenger injuries, could be avoided. Subsequently, there will be significant cost savings due to the reduction of these incidents. The study team also conducted a detailed study on deployment issues associated with the LTD BRT system and have identified a number of institutional and deployment challenges.

Stakeholder perspectives on needs and requirements were translated into system definition and preliminary functional requirements in as quantitative a manner as practical. Subsequently, preliminary technical specifications were defined based on the decomposed elemental functions for the lane assist and precision docking systems within the intended operational conditions/environment and internal and external constraints. In order to assist transit properties/implementers to select the most effective approaches and technologies for their applications, the team also developed a set of qualitative (and quantitative whenever possible) Measures of Effectiveness (MOEs) and conducted a preliminary study of safety analysis methods. The functional analysis, preliminary functional requirements and technical specifications, MOEs and safety analysis method are reported in Chapter Four. Note that the functional requirements and technical specifications are indeed preliminary, as they still needs review from broader transit stakeholders including transit operators, bus manufacturers, technology suppliers and state or local agencies that operate and maintain the infrastructure. The project tram recommends that the Federal Transit Administration and American Public Transportation Association take the lead to pursue further development of these requirements and specifications.

The need for a large-scale field testing and demonstration project was a central theme brought up by the participants throughout the workshops. The participants suggested that it should first be done as a closed track test over several months and then field tested on service routes. Representatives from participating transit agencies felt that the field operational test is essential, as previous experience suggests that it is not possible to anticipate all the possible occurrences/outcomes including all the unexpected things that other drivers might do such as cutting in front of buses and blocking bus stops. The field testing and demonstration would have the advantage of giving a better picture of operational characteristics and improvements with the introduction of lane assist and precision docking technologies. Transit representatives generally felt that, giving the conservatism of the transit industry in general, no transit agency would want to take on such a demonstration itself and it would be necessary for a demonstration to be done under the leadership of federal and state government agencies.

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Appendix A – Effects of Tight Turning Radii on Needed Lane Width

Buses equipped with electronic guidance are able to operate in narrower lanes than normal buses. Several existing electronic guidance technologies have been shown to be capable of steering buses in a 10 foot wide lane, which represents a 17 percent reduction from a "normal" 12 foot straight line segment bus lane. On turning segments, physical constraints require a wider lane than straight line segments. The sharper the curve, the wider the lane needs to be (the technical explanation of this is shown below). The following two figures show the additional lane width required as a function of turning radius for a 40 ft New Flyer single unit bus and a 60 ft articulated bus.

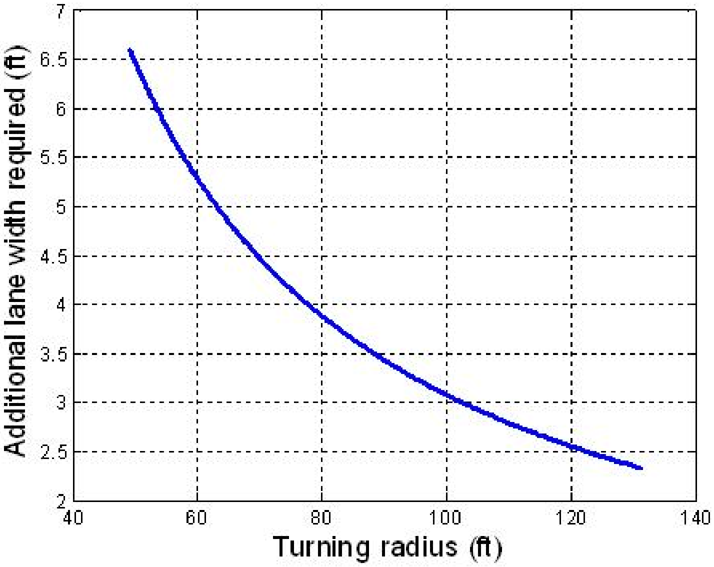

Figure A1 - Additional lane width required vs turning radius for a 40 ft New Flyer bus

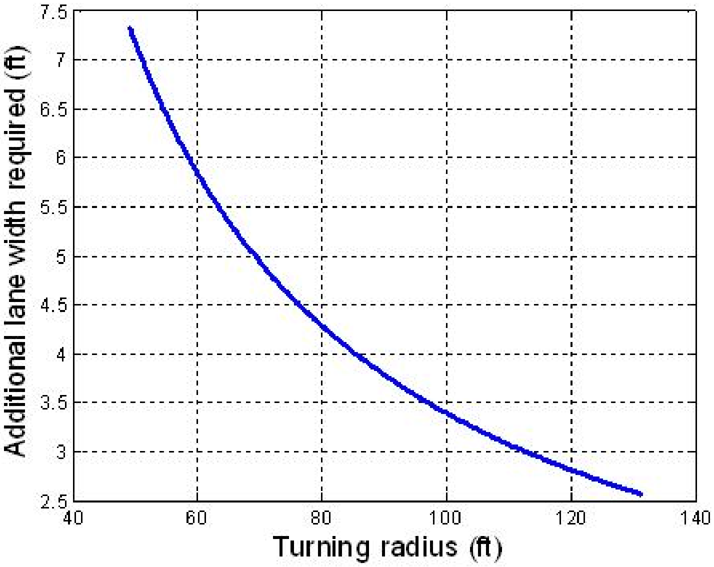

Figure A2 -Additional lane width required vs turning radius for a 60 ft New Flyer articulated bus

When the bus is in motion, one of the physical constraints it has to satisfy is a nonholonomic kinematic constraint assuming that there is no side slip of the vehicle tires. As shown in Figure A3, a is the middle point of bus' rear axle, (x, y) are a 's coordinates in a fixed reference frame. θ is vehicle's orientation angle. The nonholonomic kinematic constraint can be described by

$$\tan\theta = \frac{\dot{y}}{\dot{x}} = \frac{dy}{dx} \tag{1}$$

where $\dot{x}$ and $\dot{y}$ represent point a 's velocity components at x and y direction.

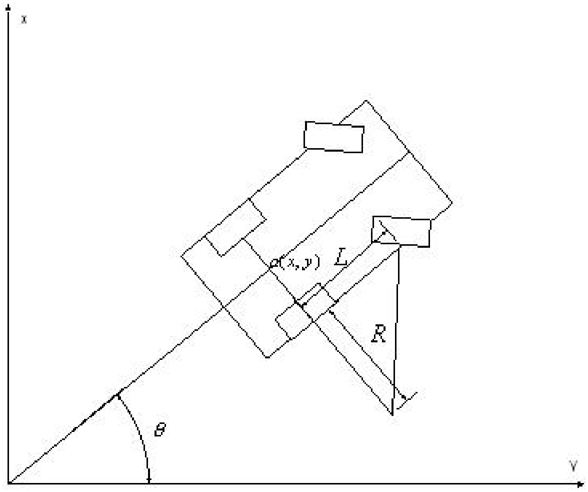

Figure A3 - Vehicle motion

One effect of such nonholonomic kinematic constraint is that the rear wheels are always inside the trajectories of the front wheels when the vehicle is turning. To further illustrate this effect, a 40 ft single unit New Flyer bus and a 60 ft articulated New Flyer bus are used as examples.

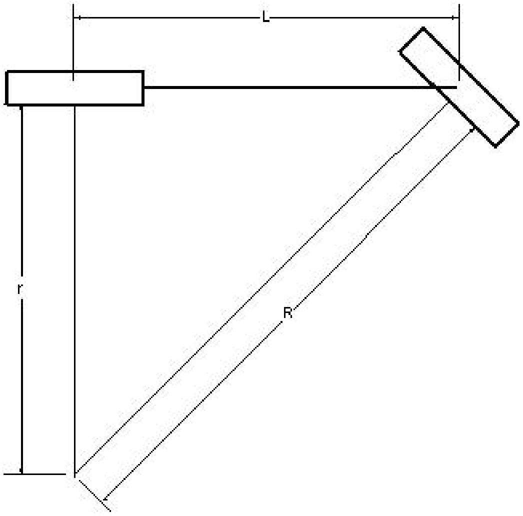

Figure A4 - Turning radius for single unit bus

Assume there is no sliding on each tire and we consider geometric relation only. As shown in Figure A4, the turning radius at the front tire is R, the turning radius at the rear tire is r and L is the wheelbase length. Then we will have following relationship:

$$R^2 = L^2 + r^2 \tag{2}$$

From (2), we have $R > r$. That means that the rear tire will always have a smaller turning radius compared with the front tire.

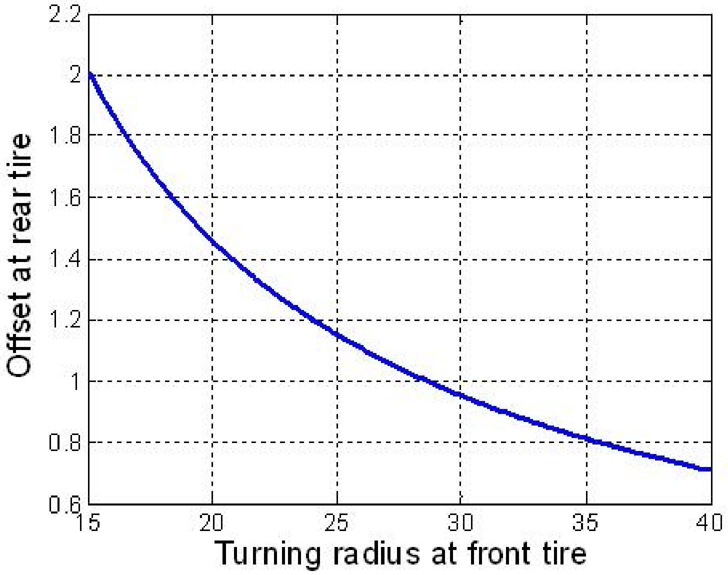

Figure A5 Offset at rear tire (m)

Figure A5 shows the offset tracking $R - r$ at the rear tire for a New Flyer 40 foot single unit bus.

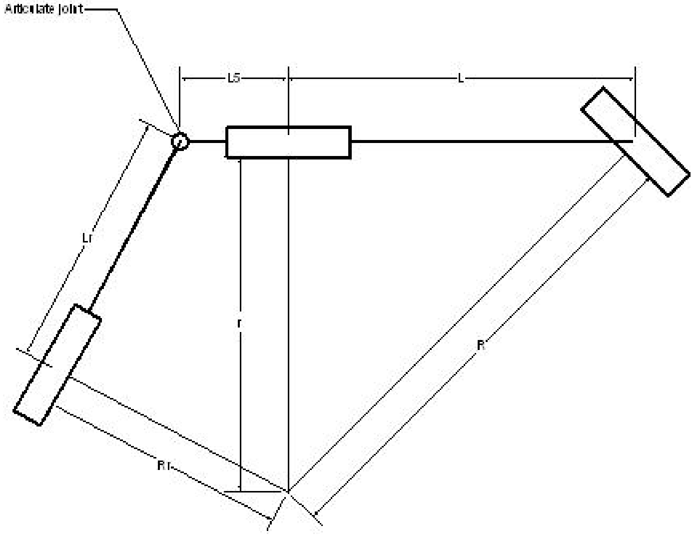

Figure A6 - Turning radius of articulated bus

As shown in the Figure A6, $L5$ represents the distance between rear wheel and articulation joint, Lr represents the distance between articulation joint and rear wheel and Rr represents the turning radius at the rear tire. With the same assumptions, we will have

$$Rr^2 = R^2 + L5^2 - L^2 - Lr^2 \tag{3}$$

Figure A7 shows the offset tracking at the rear tire for a New Flyer 60 footer articulated bus.

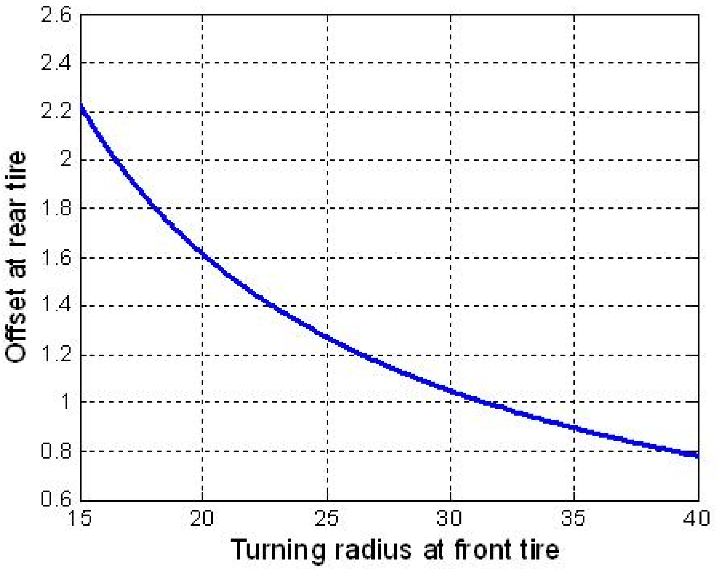

Figure A7 - Offset at rear tire (m)

Appendix B: Questions For Lane Assist Requirements Workshop

Application scenarios

What are your current and future BRT applications that may benefit from electronic guidance? Do any of the application locations contain any of the following features:

- Signalized intersection
- Toll plaza
- Locations with limited right-of-way
- Bridges
- Tunnels

In what ways do you think lane assist will be of benefit for these applications?

What role do you foresee for electronic guidance?

- Lane guidance
- Precision docking

If you foresee docking, assist, do you think that the docking would be inline or by lane-changing to a curb-side stop (S curve)?

What types of vehicles would require lane assist technology, e.g., "standard" bus (non-articulated), articulated bus, school bus?

Are there any weather conditions or physical obstacles that could conflict with the type of lane assist technologies you might employ.

Do you anticipate operating your BRT system on segregated, dedicated, or mixed traffic busways?

- Where would these busways be located?
- In median
- At curbside
- On highway shoulders
- In a completely segregated right-of-way (e.g., former rail ROW, etc.)
- In HOV lanes

If using a narrow or segregated lane, how would these lanes be separated from normal traffic lanes?

Physical barrier

- Paint/striping
- Grass, gravel, or other material
- Dedicated, separate roadway
- Rumble strips
- In-pavement lighting (similar to airport runway lights)

Do anticipated routes for narrow lanes require tight turns or turns at intersections?

Would you have the potential for conflicts between the bus in a bus-only lane and vehicles that wish to enter or exit the road e.g., vehicles that desire to exit the roadway via an exit ramp that may conflict with a bus on the shoulder?

Besides buses, what other vehicles will be allowed to use the narrow lanes e.g., police and emergency vehicles?

If a roadway/tunnel/bridge could be modified to incorporate an extra narrow lane for buses, would you pursue funding for lane assist technology?

What are the main constraints for your proposed application?

- Physical
- Political
- Financial

Operations and Driver–Vehicle Interface

Do you foresee your agency being more interested in a system that has automated steering and speed control or just automated steering? What type of factors would be considered in making such a decision?

If technology could provide reliable autonomous control of vehicles, would you consider using unmanned vehicles, or would a driver still be required?

Platooning is the technique of electronically coupling vehicles together in small groups that follow a lead vehicle. Do you see the need for bus platoons in the future? Would you accept a driver in the first lead bus and no drivers in the follower buses?

What is your current breakdown response time? If you are considering segregated lanes, what breakdown response time would be acceptable for operation in such a lane?

Do you have any thoughts or suggestions on the following methods of displaying information to the driver

- visual displays
- auditory alerts
- tactile/haptic feedback

Do you have any suggestions or thoughts on methods for transfer to/from auto control?
Driver initiated
System initiated

Do you have any suggestions on methods that can be used to keep the driver involved when the system is in automated mode?

What course of action should be followed in the event of a guidance system failure (failsafe/failsoft)?

- By system
- By driver

Implementation of any new technology brings with it the potential for a fault to occur in the system. In an electronic guidance system the following faults could potentially occur:

- The system could stop making steering control inputs
- The system could make an unexpected/unexplained input
- The system could make steering control inputs that exceed the width of the lane

For the above faults assuming that the system detects the fault do you have any suggestions or thoughts on how the driver should be notified that the system has a fault, what the driver should/could be expected to do and what the system should do?

What types of driver training programs are currently used? How frequently is refresher training given?

Do you conduct training courses internally or through outside contractors?

Do you usually select certain drivers to operate special routes or do you rotate frequently among all drivers? Do you anticipate using a specific group of drivers for BRT routes?

What are your peak morning and afternoon hours?

What is your peak and off-peak service frequency?

Cost, Benefits, and Other Decision Process

What factors are considered by your agency in determining the purchase or deployment of a “new” technology?

Is there some percentage of cost that must be offset by tangible benefits?

How are non-tangible or hard to quantify benefits such as public time savings, quality of life improvements, and environmental impacts factored in?

- Public acceptance and perception
- Experience of other transit properties using the technology
- Reliability
- Warranty
- Maintenance capabilities
- Maintenance crew training
- Deployment schedule (percentage use in fleet and expansion schedule),
- board approval, etc.

Which of the benefits that we listed in our presentation are most important to your applications? (Please rank them)

Are there any additional benefits that we missed?

Based on your past experience in technology procurement, how do you decide what you would be willing to pay?

In the case of BRT now, lane-assist later, would your agency be willing to retrofit buses with guidance systems or would you simply have it installed in new buses?

Safety and Risk Management

If the guidance technology can be shown to reduce the total number and cost of accidents, is it acceptable if this technology causes some accidents?

Given the type of system you are considering and its location relative to traffic, what is the maximum safe speed differential between buses and cars?

When adopting a “new” technology, are there specific steps in the process to address safety issues?

How can motorist violations of bus only lanes be prevented if there are no physical barriers?

At what level must a law be passed regarding lane violation (city, county, state)?

Who is involved in safety assessment and operational certification before equipment is deployed?

What are the potential issues in getting approval and certification from governing agencies?

What is the estimated time frame for going through the safety assessment and certification process?

Is there any advanced preparatory work that can be done to expedite the process or to minimize potential problems?

How do you feel your agency’s liability picture will change with the introduction of BRT and lane-assist?

Do you think there is any difference in liability implication or severity if an accident is caused by driver or by guidance system, e.g., will a guidance failure be able to be passed back to manufacturer?

What has been the total liability exposure faced by your transit agency in the past 1, 5, 10 years?

What is the process involved in determining measures to reduce liability exposure?

How does the transit agency manage its insurance plan?

Are you self-insured or externally contracted?

How are safety-related issues or risk management matters addressed by your agency, i.e., how is your risk management department structured and what is the process by which crashes and incidents are handled?

- Maintenance
- Vehicle
- How do maintenance requirements affect decisions on technology procurement?

What is the size of your vehicle and equipment maintenance staff?

What is the size of your fleet?

What repairs do you take care of in-house and which to you outsource?

Will the new system require significant changes in maintenance procedures, expertise, or expense with regard to preventative maintenance, diagnosing system problems, infrastructure (e.g., lane markings), and system calibration?

What is the current frequency of preventive maintenance and repair work needed on major bus systems?

What is an acceptable frequency for bus/technology maintenance or repair as compared to current procedures?

What types of training programs are carried out for maintenance crew? How often? Are they conducted through external institutions or internal programs?

What experience do you currently have with technology such as:
Smartcard

- Automated passenger counter
- Automated fare collector
- Fare kiosk
- Automatic Vehicle Locator
- Security camera
- Mobile Data Terminal

Who would need to maintain infrastructure (e.g., agency, city, state)?

How can the road or trackway be kept clear of obstacles and debris and whose responsibility is this?

Deployment and Institutional Issues

Has your agency worked with other transportation organizations (transit agencies, MPOs, local DOTs) in your local and/or regional area on projects relating to the implementation of new technologies or new services? If yes, how important to the success of these projects is inter-jurisdictional coordination and communication?

How easy or difficult do you think it could be to “sell” or market the changes associated with BRT and/or its associated lane assist systems? Will special or customized approaches have to be taken, such as educating motorists and pedestrians on interacting with lane assist system operations? How will the public react to the loss of parking?

How do the passengers that ride your buses or local/regional media currently view your agency in terms of the service it delivers, its current performance and its reputation?

If your agency has already implemented advanced technology systems, what was the level of passenger acceptance of such systems? Was it immediate or was there a need for a “breaking-in” period that could offer lessons learned for implementation of new systems, such as transit lane assist?

Do you have the authority to modify the infrastructure?

Technology Options

What technologies are you considering and why?

What technologies did you review and why did you reject the other technologies?

Can you explain more about the decision-making process your agency used to accept/reject other technologies?

What past experience does your transit agency have in adapting something similar in scale to lane assist?