Phased Implementation of Lateral Guidance Systems in High-Occupancy-Vehicle Lanes

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Phased implementation of advanced lateral guidance systems in high-occupancy-vehicle lanes with exclusive right-of-way, or transitways, is described. The three incremental systems are steering assistance information systems, partially automated lane-keeping systems, and fully automated lateral control systems. Capabilities, functional requirements, system structure, and components for these systems are presented. Experiments and tests conducted at the University of California's PATH program indicate that the discrete magnetic roadway reference system appears to be a possible technology for applying all three incremental systems in transitways. Potential safety and capacity benefits of the three incremental systems in transitways are quantified.

Knowing the vehicle lateral position is important when operating vehicles on roadways. At this time, this knowledge and the task of keeping vehicles in the travel lane are drivers' responsibilities. Emerging lateral guidance and control systems could help to maintain the vehicle position along the lane center more precisely and reliably than drivers can. Therefore, these systems provide a means for improving the highway safety, particularly when drivers are inattentive or are driving in poor visibility. Furthermore, it is possible that control of vehicle lateral displacement may lead to reductions in the lane width requirement without compromising traffic safety. If so, additional travel lanes could be created and added capacity could result within existing rights-of-way.

Large-scale implementation of lateral guidance and control systems to enhance both highway safety and capacity is a long-term goal, and its progress requires incremental technology development and implementation, initially on a limited scale in existing highway facilities. High-occupancy-vehicle (HOV) lanes, which are separated from the freeway main lanes by permanent barriers and have controlled access and egress, are considered to be good candidates for this purpose. Implementation in these HOV facilities, which are generally known as transitways, could be a stepping stone to the eventual networkwide implementation because

- This limited-scale deployment of the new technology is likely to be less complicated than the networkwide deployment.
- The barriers separating transitways from the main lanes and the transitways' controlled access and egress could help to ensure maximum safety of the new system without on-the-road experience.
- This limited-scale deployment allows collection and evaluation of data concerning on-the-road system performance as well as driver responses to the use of driver-assisted devices. It could help to stimulate technology improvement toward full maturity.

Lateral control technology is not new. In fact, it has been investigated by researchers since the 1950s (*1–8*). However, research and development (R&D) efforts to apply lateral guidance and control systems in the highway environment are still in the very early stages. This paper examines an implementation strategy, a system structure, and the functional requirements of lateral guidance and control systems that could be deployed in existing transitways. It also assesses potential traffic and safety impacts due to this deployment.

OBJECTIVE

The objectives of this paper are to

- Describe lateral guidance and control systems for incremental implementation, from the near term to the long term, in existing transitways; and
- Assess the safety and traffic impacts of these incremental systems.

TECHNOLOGY OVERVIEW

The literature on vehicle lateral guidance and control systems emphasizes systems that perform the lane-keeping function. Such systems require roadway reference and sensing, vehicle controller, and vehicle actuation technologies. An overview of these component technologies is presented.

Roadway Reference and Sensing System

The roadway reference and sensing system requires both roadway reference and in-vehicle sensing devices. The roadway reference provides information about the lane lines or road edges. Possible roadway references include painted lines, raised

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pavement markers, and wires or magnetic markers embedded in the pavement to transmit electromagnetic or magnetic signals. The in-vehicle sensing device consists of sensors to receive signals from the roadway reference. These signals are then converted into information about the vehicle's lateral position. Depending on the kind of roadway reference and sensing technology employed, additional information such as upcoming roadway geometry (known as preview information) could also be obtained.

Roadway reference and sensing systems could be based on a number of technologies—for example, electromagnetic, radar, acoustic, optical (including vision-based), and magnetic. To date, these technologies have been investigated primarily in simulations and laboratory experiments. The two most promising technologies for large-scale applications in the highway environment appear to be vision-based systems and those using discrete magnetic markers (*9*).

Vision-Based Systems

Roadway reference and sensing systems based on vision-sensing technologies (e.g., video cameras) could directly acquire information on both the vehicle lateral position and the upcoming roadway geometry from existing lane lines or roadway delineation. Therefore, they are vehicle "autonomous" systems, which do not require special installation of roadway reference. At this time, there are uncertainties about applying vision-based systems on the highway because of the possible effects of debris, adverse weather, and light condition on performance; the requirement of large amounts of data in order to provide real-time guidance; and unknown reliability and costs of the in-vehicle data processing capability (*9*). R&D efforts to develop vision-based systems and their information-processing capability have been reported in the literature (*10–12*). However, whether these systems would work in diverse real-world weather and operating conditions remains largely unknown.

Discrete Magnetic Marker Systems

These roadway reference systems use small magnetic markers buried vertically in the center of the lane to provide the roadway reference. Magnetic fields from these markers are picked up by magnetic-type sensors installed on the vehicle. Relative to vision-based systems, discrete magnetic reference systems are not sensitive to debris or weather and light conditions (*9*). They could also provide preview information about upcoming road geometry by means of some magnetic coding scheme. However, they would require special installation of magnets in the pavement.

Other features of the discrete magnetic reference system include (a) the roadway in which the magnets are installed does not require electrification; (b) any magnetic damage or fault would affect the system locally but not the entire network, and repairs or replacements of the damaged magnets could be done quickly; and (c) the system could offer flexibility in that it is possible to install temporary markers to lead vehicles around construction zones, even without having to remove the markers already in place (*9*).

This paper focuses on applications of lateral guidance and control systems that use the discrete magnetic reference system in existing transitways. Research on such systems has been ongoing at the University of California's PATH program since 1987.

Vehicle Controller

Vehicle controllers for lane-keeping systems usually consist of computers and control algorithms. The computers process sensory information and execute control algorithms in real time. The control algorithms may include "feedback" and "feedforward" components. The feedback control algorithm receives information about the vehicle status with respect to the lane center and corrects local lateral deviations of the vehicle in an incremental manner. The feedforward control algorithm receives information on upcoming road geometry and issues commands to the steering actuation unit, in preparation for negotiating the change in roadway geometry ahead.

Vehicle Actuation Unit

The vehicle actuation unit receives steering commands from the vehicle controller for use in turning the steerable wheels. There are no commercially produced actuators for lane-keeping systems at this time, and research on such steering actuators is sparsely reported.

PHASED IMPLEMENTATION OF LATERAL GUIDANCE AND CONTROL SYSTEMS IN TRANSITWAYS

A possible strategy for implementing lateral guidance and control systems that use the discrete magnetic reference technology in existing transitway facilities is investigated. Implementation of these systems could follow a building-block approach, initially starting with systems that are relatively limited in terms of the degree of driver-assisted tasks. Three implementation phases are suggested; each is to be built on the preceding phase as far as possible. The three incremental systems are

- Phase 1: Implementation of steering assistance information systems (SAISs), essentially lateral warning systems, to enhance driver perception and warn drivers when vehicles are unintentionally encroaching on the lanes or drifting outside the lane; drivers would still perform all steering-related tasks themselves.
- Phase 2: Implementation of partially automated lane-keeping systems (ALKSs) to control the vehicle position along the lane center, with manual override for lane changes.
- Phase 3: Implementation of fully automated lateral control systems (ALCSs) that automatically perform lane-keeping, lane changing, merging, and diverging; the system could take over lateral steering tasks from the driver.

PHASE 1: STEERING ASSISTANCE INFORMATION SYSTEMS (SAISs)

Capabilities, functional requirements, system structure, and components of SAISs (that use the discrete magnetic reference and sensing system) to be implemented in transitways in Phase 1 are described. In addition, potential traffic and safety impacts due to the implementation of SAISs are also presented.

Capabilities of SAISs

It is foreseen that adoption of SAISs by transitway users will be voluntary. SAISs could provide the following real-time information to drivers:

- Vehicle lateral position: SAISs could provide information to drivers about vehicle lateral position with respect to the lane center. This is true in normal conditions, with poor or invisible lane marking, in poor-visibility conditions (e.g., nighttime), and in adverse weather.
- Edge warnings: SAISs could warn drivers when vehicles are inadvertently encroaching on adjacent lanes or drifting outside the lanes. These inadvertent vehicle maneuvers, which frequently result from driver fatigue, inattentiveness, or sleepiness, may be corrected by drivers if they receive warnings soon enough.
- Information about upcoming road geometry: SAISs could give drivers information about changes in the upcoming road geometry (e.g., road curvature). Therefore, they could help to better prepare drivers to make required steering actions sooner.

Functional Requirements

Functional requirements of new systems that have not yet been configured are defined as desired capabilities or performance goals that the systems should be targeted to achieve. Functional requirements for SAISs, with respect to the deployment in transitways, include

1. When an SAIS mistakenly gives a warning that the vehicle is drifting outside the lane when it actually is not, this warning is said to be a false alarm. Although false alarms per se may not be hazardous, a high rate of false alarms could erode user confidence. Effects of the rate of false alarms, and thus an acceptable false-alarm rate, for SAISs have not been explored. This knowledge is needed before reasonable rates of false alarms can be specified for practical SAISs. Nevertheless, it is believed that a very low rate of false alarms may be essential for public acceptance of the device.
2. When an SAIS fails to detect the vehicle drifting out of the lane, it is said to have a system "miss." System misses could be hazardous enough to result in traffic accidents. Therefore, system misses should be eliminated through the system design. Possible means for accomplishing this include the incorporation of sufficient redundancies for weak links within the system and the elimination of failures that could result in adverse consequences through systemic design.
3. Correct warnings on required steering correction actions (e.g., steer left or right) must be ensured. The incorporation of redundancies for weak links could help to enhance this system accuracy.
4. Warning signals to drivers must be effective, both when drivers are alert and when they are fatigued or inattentive.
5. The discrete magnetic reference and sensing system must be robust in all weather and operating conditions.
6. Installation and replacement of magnetic markers should be simple and it can be carried out quickly, because pavements are periodically resurfaced as part of regular maintenance. The magnetic markers should require minimal maintenance, and their life cycle should be compatible with that of the pavement.

System Structure and Components

A conceptual structure of near-term SAISs to be implemented in transitways is shown in Figure 1. Principal components of

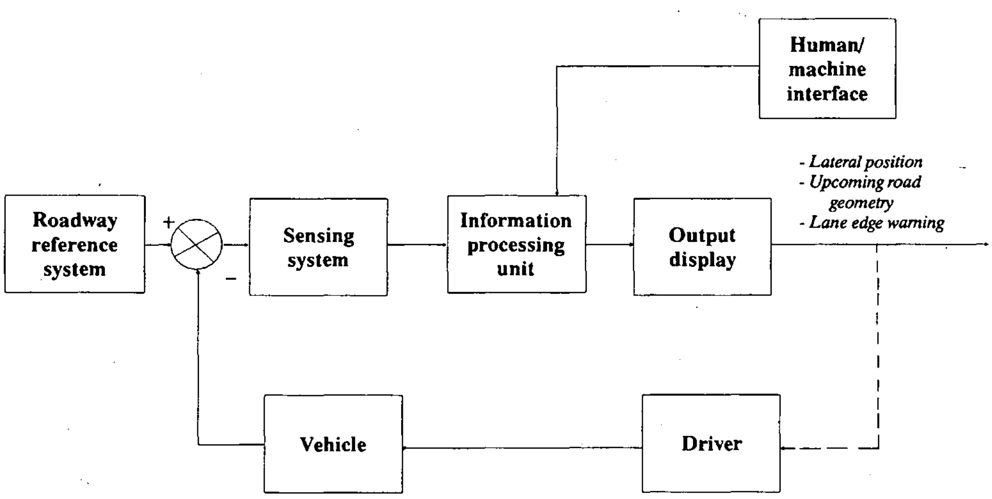

FIGURE 1 Steering assistance information system.

these SAISs include magnetic markers and an in-vehicle magnetic-sensing device (collectively called the magnetic roadway reference and sensing system), information processing unit, and human-machine interface unit.

Discrete Magnetic Reference and Sensing System

The discrete magnetic reference and sensing system that is being researched at PATH consists of a series of small permanent magnet markers. Each marker is 2.5 cm in diameter and 10 cm long and buried vertically in the pavement. These magnetic markers could be installed in single file along the lane center, with spacing of at least 100 cm. Dynamic tests on this system are being conducted at PATH to determine the effects of the magnetic-marker spacing on system performance. The magnetic fields provide information about the vehicle lateral position with respect to the lane center. In addition, by alternating the polarities of the magnetic markers, a series of binary information (0,1) can be encoded to provide information about upcoming roadway geometry. Codes could be checked and corrected to ensure the reliability of the preview information so obtained.

Magnetic signals generated from the magnetic markers are picked up by the on-vehicle sensing device. In this regard, magnetic sensors (or magnetometers) designed to be compatible with the magnetic markers can be installed under the front bumper of the vehicle. The signals acquired by the magnetometers are then converted into vehicle lateral deviation by the information processing unit. Tests of magnetometers conducted at PATH indicate that they are capable of acquiring signals at very low speeds (zero or close to zero) as well as at highway speeds (*5*). The magnetometers used in these tests are off-the-shelf devices. Magnetometers to be used by vehicles in transitways may have to be specially designed to ensure high reliability and low cost.

Tests were also conducted at PATH to measure signals from the magnetic reference and sensing system when pavements were covered with water and ice. Test results indicate that the signals are not degraded by these adverse conditions (*5*). Findings from experiments and tests conducted at PATH to date indicate that the discrete magnetic and sensing system appears to be a possible system for applications in transitways. Future tests of the discrete magnetic reference and sensing system will continue at PATH for roadways that have steel reinforcements.

Magnetic markers are relatively inexpensive. Those used in experiments at PATH are produced in small quantities and cost about $2 to $3 each. Production volumes of these magnets are likely to lower their cost. Magnetic markers are also relatively easy to install. Existing construction technologies (including the advanced robotics technology) could be adapted for the magnet-marker installation.

Information Processing Unit

The information processing unit consists of an onboard computer to process signals from the magnetometer and to produce output information for the drivers. An algorithm to process signals from the magnetometer has been developed at PATH (*5*). In addition, methods to overcome interference problems in the lateral position measurement—the overlapping with the earth's magnetic field, high-frequency magnetic noise generated by the vehicle engine system, and spontaneous vertical movements of the vehicle—were also developed and tested (*5*). This algorithm has since been tested at PATH, in bench tests, as well as in track tests using a scaled vehicle (1 m long and 0.5 m wide) and a full-size experimental vehicle. The test results indicate that this algorithm works satisfactorily.

Human-Machine Interface Unit

Information and warnings to drivers can be visual, audio, or both. For example, upcoming road curvature and the vehicle lateral position relative to the lane center could be displayed visually. Audio warnings could be given to the driver when the vehicle moves outside the lane. Warnings will not be given during deliberate lane-changing maneuvers. In this regard, the SAIS's on-off switch and the turn-signal switch could be integrated to deactivate the SAIS during a lane-changing maneuver and to resume the SAIS as soon as the lane change is complete. Research is needed to determine effective output display modes for practical SAISs.

Estimation of Potential Safety Benefit of SAISs

Implementation of SAISs in transitways is likely to have little direct effect on the transitway flow or capacity. However, it may bring about reductions in certain kinds of transitway accidents.

It is conceivable that SAISs could help to reduce frequencies of run-off-road and sideswipe accidents in transitways. This potential safety benefit is estimated using in-depth examinations of hard-copy accident reports as opposed to analyses of computerized accident data. This is because accidents on transitways could be difficult to identify from computerized data. Further, computerized accident data are not likely to have sufficient details for determining whether the accident outcome could be influenced by the use of new devices.

The transitway mileage in any one state is usually small. This plus the fact that accidents in transitways are even rarer events than accidents on the mainline make it necessary to obtain transitway accident data from a number of states in order to obtain a reasonable sample size. Hard-copy reports of transitway accidents from California, Houston (Texas), and Virginia (the I-66 transitway) are available for the analysis. The reports from California represent all reported transitway accidents for 4 months in 1990; the reports from Houston represent all reported transitway accidents for 12 months in 1990; and the reports from Virginia represent transitway accidents in the I-66 facility for 6 months in 1990. In all, 72 hard-copy reports of transitway accidents were analyzed.

For each commuter-lane accident, the in-depth analysis of the hard-copy accident report follows the following steps:

1. All information in the accident report, including the accident diagrams, is critically examined to identify a sequence of events and actions that culminated in the accident. This

sequence of events is useful for determining possible points of intervention by the new device.

2. Probable contributing factors of that accident are identified from all the evidence available in the accident report.

3. An evaluation is performed to see whether at least one of the identified contributing factors may respond to the new device. A view is taken that if one contributing factor could be eliminated by the new device, the new device would be considered useful as a possible accident countermeasure.

The results of this safety analysis indicate that SAISs could be useful as countermeasures for up to 8 percent of transitway accidents. These are accidents in which vehicles drift outside the travel lanes and strike the barriers or channelization at highway speed as a result of driver inattentiveness.

It must be noted that this estimated safety benefit is likely to be an upper-bound benefit for the following reasons:

1. Although it is foreseen that the adoption of SAISs will be on a voluntary basis for transitway users, the safety analysis assumes that all transitway users are equipped with SAISs. If SAISs are adopted by only a fraction of transitway users, the estimated benfit must be proportionally reduced.
2. In the accident analysis, it is assumed that SAISs will perform as they are expected to.
3. It is assumed that there would be no changes in driver behavior due to SAIS adoption.
4. The accident analysis cannot take into account the extent to which the use of SAISs may introduce new kinds of accidents, for example, those related to system malfunctions or failures. This determination requires on-the-road data that are not currently available.

PHASE 2: AUTOMATED LANE-KEEPING SYSTEMS

In Phase 2, automated lane-keeping systems (ALKSs) could be introduced in transitways. As with SAISs, the ALKSs investigated in this paper also use magnetic markers as the roadway reference system. Capabilities, functional requirements, system structure and components, and potential impacts of these ALKSs are described below.

Capabilities

ALKSs perform partially automated vehicle lateral control—that is, when the system is activated, it would automatically control the vehicle lateral position. However, this lane-keeping function could be temporarily deactivated when the driver engages the turn signal to perform manual lane-changing in transitways with two or more lanes. As soon as the manual lane change is complete, the automatic lane-keeping will be resumed.

It is expected that the adoption of ALKSs in Phase 2 by transitway users will be voluntary, and at least initially will not be accompanied by reductions in the lane width. Phase 2 is considered a desirable step before the implementation of fully automated lateral control systems because it would allow drivers to become familiar with using automated devices and learn to share tasks with them and it would allow on-the-road data concerning system performance to be collected for use in developing long-term fully automated lateral control systems.

Functional Requirements

In addition to the functional requirements previously described for SAISs, further functional requirements for the partially automated ALKSs include

1. ALKSs should be fail-safe systems. That is, system failures that could result in catastrophic consequences should be eliminated through the system design. Should system failures occur, they must not lead to a loss of vehicle controlability.
2. In this phase, drivers of equipped vehicles should have the option of turning the device on or off as they wish.
3. ALKSs must perform the lane-keeping task with good accuracy. In this regard, the allowable vehicle deviation (for ride quality, safety, and efficiency reasons) is being researched at PATH. Nevertheless, as an absolute minimum, ALKSs must be able to steer vehicles wholly within the lane boundaries.
4. ALKSs should have reasonably good ride quality in order to encourage system adoption. There are trade-offs between lane-keeping accuracy and ride quality that need to be addressed by further research.

System Structure and Components

ALKSs and SAISs share a number of components. Figure 2 shows a conceptual structure and major components of the ALKSs for Phase 2. The roadway reference and sensing system and information processing unit are identical to those for SAISs. In addition, ALKSs also require a battery of vehicle sensors, a vehicle control unit, and a steering actuator. It also requires a human-machine interface unit that is different from that for an SAIS. These additional components for ALKSs are described.

Vehicle Sensors

Vehicle sensors include accelerometers, angular-rate sensors, steering-angle sensors, and speed sensors for measuring vehicle lateral accelerations, yaw rates, actual ground wheel steering angles, and vehicle speeds, respectively. These technologies are largely available. However, more research is needed to assess whether their resolution and accuracy will be sufficient for applications in transitways.

Vehicle Control Unit

The vehicle control unit generates steering commands in accordance with some ride-quality and steering-accuracy requirements. This unit could share a computer with the information processing unit. Vehicle control algorithms would incorporate the "intelligence" that is capable of determining the vehicle status and environmental conditions for use in issuing steering commands approrpiate for prevailing condi-

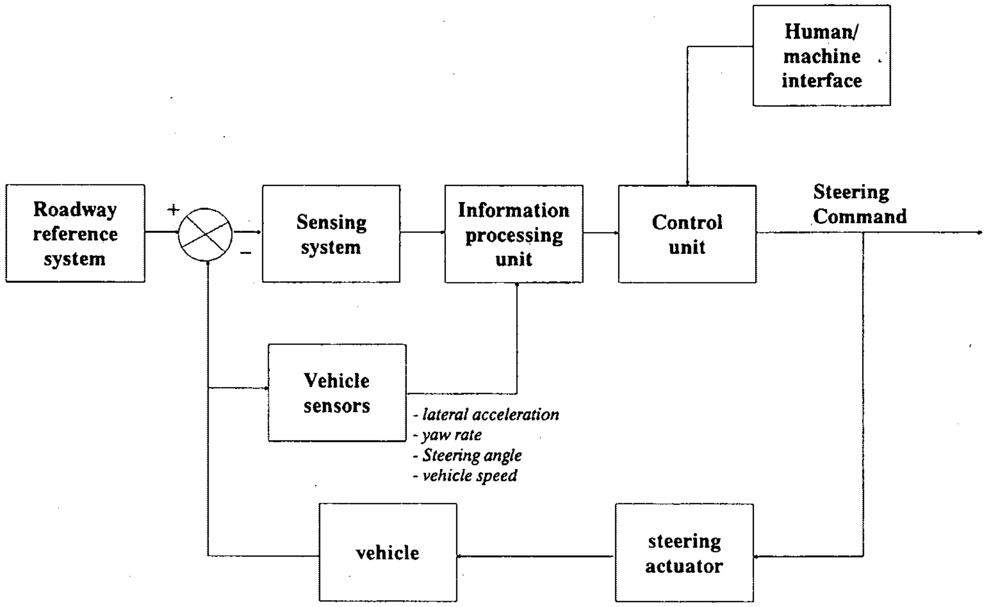

FIGURE 2 Automated lane-keeping system.

tions. The vehicle control unit could also incorporate safety logics to coordinate the transfer between automatic control and manual steering.

Both feedback and preview control algorithms have been developed at PATH (*7*, *8*). The feedback control algorithm generates steering commands from the feedback information (which includes the vehicle lateral position, lateral accelerations, and yaw). The preview control algorithm incorporates both the feedback and feedforward control components. The latter component estimates anticipatory steering angles from the information on upcoming road geometry.

Experiments on ALKSs were conducted at PATH (*13*). These experiment used a scaled vehicle (1 m long and 0.5 m wide), feedback and feedforward control algorithms, and the magnetic reference and sensing system. The test vehicle was equipped with electrical driving, a steering motor, a computer, and the aforementioned vehicle sensors. Information about upcoming roadway geometry was coded in the magnetic markers. The vehicle's maximum speed during the tests was 3 m/sec. In these tests, a maximum vehicle lateral displacement of ±20 cm was observed. Further, the test results also indicate that lateral accelerations could be controlled within an acceptable level required for good ride quality. Therefore, it appears that ALKSs using the discrete magnetic reference and sensing system are plausible systems for applications in transitways. PATH is planning to conduct further tests with a full-scale experimental vehicle. In this regard, a 700-m test track has been constructed at the University of California at Berkeley. These tests are expected to be completed in 1992.

Vehicle Actuation Unit

The steering actuator unit is used to operate steerable wheels to achieve required steering angles. These actuators, which may be hydraulic or electric servos, receive commands from the vehicle control unit. Research is needed to determine the maximum allowable steering angle for lane-keeping. One possible solution is to limit the maximum allowable steering angle of ALKSs to the minimum radius of curvature commonly recommended for the highway design.

Human-Machine Interface Unit

This unit is different than the one used in SAISs. For ALKSs, it is used to turn the automatic steering on and off. This interface unit can be designed to perform a number of functions. For example, the ALKS's on-off switch and the turn-signal switch could be integrated to facilitate manual lane-changing, as follows: this integrated switch could temporarily turn off the automatic lane-keeping when a lane-changing maneuver is taking place and resume the automatic lane-keeping once the maneuver has been completed. The interface unit could also incorporate a feature that would permit the driver to select ride-comfort levels versus tracking errors.

Research on human factors and the safety design of the human-machine interface for ALKSs is needed.

Impacts

The Phase 2 implementation of ALKSs could result in reductions in certain kinds of transitway accidents. Estimation of this safety benefit is presented.

Estimation of Safety Benefit of ALKSs

With the aid of ALKSs, the lateral position of equipped vehicles could be automatically controlled. This could eliminate driver errors of misjudgment in vehicle steering due to driver fatigue or inattentiveness; poor-visibility conditions; pavements covered with debris, water, mud, or snow; poor roadway delineation; or strong crosswinds. The previously mentioned in-depth analysis of hard-copy transitway accident reports indicate that ALKSs in Phase 2 could be useful as countermeasures for about 18 percent of transitway accidents, as follows:

- The 8 percent of transitway accidents for which the SAISs in Phase 1 are applicable as countermeasures;
- An additional 7 percent of transitway accidents that are run-off-road accidents on water-covered or icy pavements at highway speed, in which vehicles finally strike the barriers; for these accidents, the drivers did not state that they had actually applied brakes before running off the lane. It is not possible for the authors to determine, from the information available in the accident reports, how many of these accidents actually involved braking. ALKSs could be beneficial for those that do not involve braking, and they could also lower the probabilities of some accidents that involve braking.
- Another 3 percent of transitway accidents, which involve tire blowout that causes the vehicles to strike the barriers; that is, the probabilities of striking the barriers as a result of the tire blowout may be lower with ALKSs than without ALKSs.

The estimated accident benefit of ALKSs is likely to be an upper-bound benefit for the same reasons mentioned for the estimated safety benefit of SAISs.

Traffic Impact of ALKSs

The implementation of ALKSs in Phase 2, which is not accompanied by reductions in the lane width, is not expected to have significant direct impacts on the transitway flow rate or capacity. A possible exception might be the application in exclusive bus lanes (i.e., lanes specially reserved for buses) that have no shoulder or lane width smaller than 12 ft. If all the buses in the facilities are equipped with ALKSs, it is conceivable that ALKSs could help to counter the adverse effect, due to the lack of lateral clearance and narrow lanes, on the flow rate. ALKSs could eliminate the need for large lateral clearance between the vehicle and the roadside objects, which is deemed important for maximizing the flow rate under manual driving. The *Highway Capacity Manual* (HCM) documents a procedure for quantifying adverse effects due to the lack of lateral clearance on the flow rate (*14*). Based on this HCM's procedure, and if the ALKSs are assumed to be able to eliminate the need for full lateral clearance, the practical flow rate in single-lane bus lanes with no shoulder could increase by up to 13 percent. However, in the absence of actual on-the-road data concerning the use of ALKSs, human-factors research is required to verify this assumed benefit.

PHASE 3: FULLY AUTOMATED LATERAL CONTROL SYSTEMS

In Phase 3, long-term fully automated lateral control systems (ALCSs) could be introduced in transitways. Capabilities, functional requirements, system structure and components, and impacts of ALCSs are described.

Capabilities

ALCSs could take over the lateral steering of the vehicle. As with the Phase 2 ALKSs, ALCSs are capable of automated lane-keeping. In addition, ALCSs could also make other steering-related maneuvers, such as lane changes and merging. These additional automated capabilities call for the integration of additional devices. Further, all transitway vehicles would have to be equipped and the operating status of their ALCSs checked before entering the transitway to prevent failures due to equipment malfunctioning. With the mandatory system adoption by transitway users, significant lane-width reductions for the transitway would be possible without degrading traffic safety within the transitway.

Functional Requirements

Functional requirements for ALCSs are similar to those for the Phase 2 ALKSs, with the notable exceptions being the elimination of the manual override for lane changes and the driver option to turn the system on and off. From the safety perspective, such manual override and the on-off switch option appear to be undesirable for ALCSs. Further research is needed to determine if these features could be allowed in ALCSs.

System Structure and Components

Long-term ALCSs are the extension of ALKSs. Therefore, ALCSs would have all the components of the ALKSs plus some additional ones. As a minimum, the deployment of ALCSs in transitways would also require information links between individual transitway vehicles to facilitate automated lane-changing and merging maneuvers. These information links may be vehicle-to-vehicle or vehicle-and-roadside communication systems. Figure 3 shows a conceptual structure and components of the ALCSs.

Impacts

Primary impacts of the implementation of Phase 3 are reductions in frequencies of transitway accidents and increases in the transitway capacity. Other benefits include possible reductions in construction costs of future transitways, since smaller rights-of-way would be required. Also, when ALCSs are adopted, transitways can be constructed in locations where existing rights-of-way are currently not wide enough under existing transitway design guidelines.

Estimation of Safety Benefit of ALCSs

Similar to the ALKSs in Phase 2, ALCSs could eliminate driver error in lane-keeping, thus reducing accidents caused by such errors. In addition, the automated lane-changing and merging capabilities of ALCSs could also reduce the number of accidents related to lane-changing maneuvers in transitways. Results from the previously described in-depth analysis of

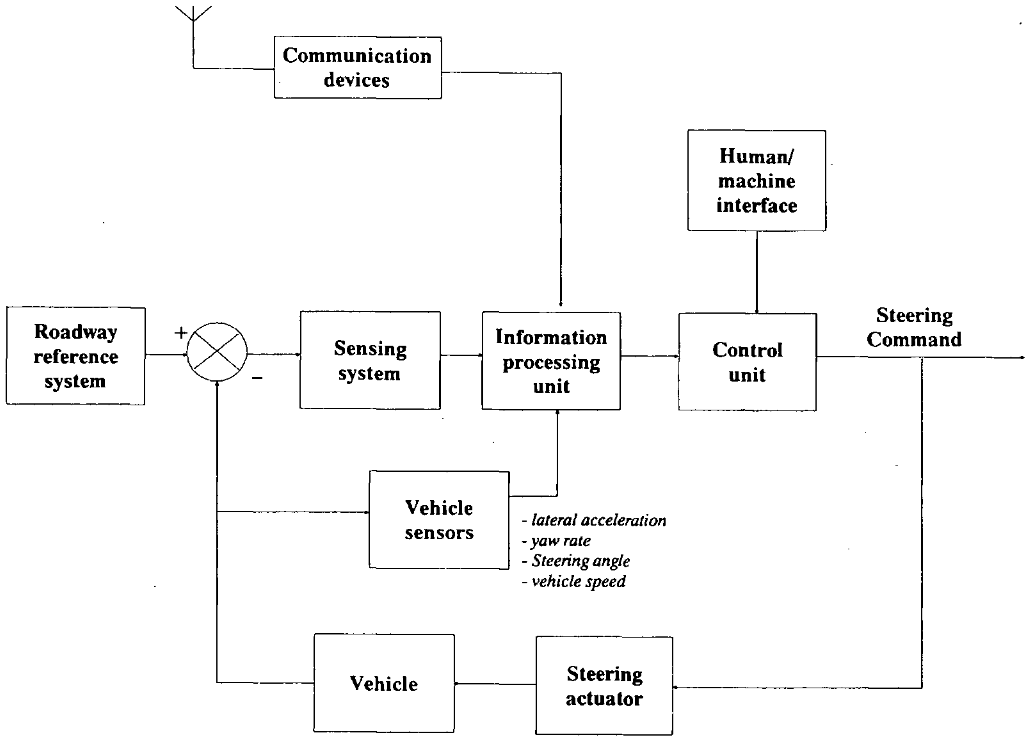

FIGURE 3 Fully automated lateral control system.

transitway hard-copy accident reports indicate that ALCSs could be useful as countermeasures for up to 24 percent of transitway accidents. Of these, 18 percent are the accidents for which the ALKSs in Phase 2 could be beneficial. The remaining 6 percent are accidents that occur during lane-changing maneuvers in transitways.

Estimation of Capacity Benefit of ALCSs

Adopting ALCSs could significantly increase transitway capacity if lane width could be reduced and additional travel lanes created within the existing right-of-way. This capacity increase is possible for existing transitways with at least two travel lanes. For most existing single-lane transitways, the lane-width reduction due to the use of ALCSs is not likely to be enough to create an additional travel lane. Nevertheless, small increases in the flow rate for single-lane transitways are possible if they currently have no shoulder or travel lanes less than 12 ft.

From the HCM's procedure for quantifying the effects of lateral clearance on the flow rate, possible increases in transitway capacity due to the Phase 3 implementation for various transitway configurations are estimated, as shown in Table 1. Table 1 also shows estimated changes in the transitway flow rate for the level-of-service (LOS) C as a result of adopting ALCSs. Estimates in Table 1 are based on the assumptions that transitway traffic is composed of 10 percent buses and 90 percent passenger vehicles and that the adoption of ALCSs could eliminate the need for the 12-ft lane width and full lateral clearance that are recommended in the HCM for flow-rate maximization under manual driving.

Table 1 indicates that, as a result of Phase 3 implementation,

- Practical capacity for single-lane transitways with no shoulder could increase by up to 14 percent.
- Practical capacity for existing two-lane transitways could increase much more substantially, when the use of ALCSs leads to reductions in the lane width and the creation of an additional lane (or lanes) within existing rights-of-way. Capacity increases of up to 47 percent and 60 percent could result for existing two-lane transitways with and without shoulders, respectively.

SUMMARY AND CONCLUSIONS

As with most intelligent vehicle-highway systems, lateral guidance systems are likely to provide the greatest safety and capacity benefits when implemented on most roadways in a network. However, networkwide implementation of fully automated lateral control systems is a very long term goal, and its progress requires incremental technology development and applications in existing highway facilities. Phased implementation of lateral guidance and control systems in existing transitways could be a stepping stone to networkwide implementation.

Phased implementation of such systems could begin with transitway users' adopting steering assistance information systems, which are essentially warning systems. Next, ALKSs

TABLE 1 Expected Capacity and Flow Rates at LOS C Before and After ALCS Adoption

HOV-Lane Configuration		Practical Capacity[e] (vph)	Flow Rate at LOS C[e] (vph)
BEFORE:	Existing 1-lane HOV facilities with no shoulder[a]	1,400	1,100
AFTER:	Same	1,600	1,300
BEFORE:	Existing 1-lane HOV facilities with shoulder[b]	1,600	1,300
AFTER:	Same	1,600	1,300
BEFORE:	Existing 2-lane HOV facilities with no shoulder[c]	3,500	2,600
AFTER:	3-lane HOV facilities with no shoulder[f]	5,600	4,500
BEFORE:	Existing 2-lane HOV facilities with shoulder[d]	3,800	3,200
AFTER:	3-lane HOV facilities with shoulder[f]	5,600	4,500

(a) 12-foot lane
(b) 12-foot lane, 5-8 foot lane
(c) 24-26 foot pavement
(d) 24-26 foot pavement, 5-8 shoulder
(e) Assuming 10 percent buses
(f) **New facilities with ALCSs have 3 lanes, two 8-foot lanes for automobiles and one 10-foot lane for buses plus automobiles**

could be introduced in transitways to provide automatic lane-keeping control with manual override for lane changes. Finally, ALCSs could be introduced in transitways to take over lateral steering tasks: lane-keeping, lane-changing, merging, and diverging.

Experiments and track tests conducted since 1987 at the University of California's PATH program on the discrete magnetic roadway reference indicate that it is a possible technology for applications of all three incremental lateral guidance and control systems in transitways.

Analyses performed in this paper indicate that the limited-scale implementation of SAISs and ALKSs in transitways could have safety benefits. The deployment of SAISs and ALKSs in transitways could reduce transitway accidents by as much as 8 and 18 percent, respectively. The implementation of ALCSs in transitways could reduce transitway accidents by as much as 24 percent. Further, if the lane width could be reduced as a result of adopting ALCSs, the capacity of two-lane transitways could be increased by 50 percent or more.

Even though the SAISs proposed in this paper are considered to be relatively near term systems for implementation in the highway environment, a significant amount of R&D remains to be completed or initiated before technology demonstration in transitways could take place. Principal R&D activities to be completed include

- Track tests of the SAISs using full-scale vehicles in real-world conditions;
- Tests to assess the compatibility between the discrete magnetic roadway reference and sensing system and existing roadway infrastructure, particularly the influence of steel reinforcements on the magnetic fields;
- Assessments of the cost-effectiveness of magnetometers; and
- The method in which warnings can be effectively and safely provided to drivers.

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