



## Lane changing with look-down reference systems on automated highways

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### Abstract

Automated lane changing is a vital component of the steering control system for automated vehicles. The most important requirements of such maneuvers are smoothness and robustness. Look-down sensing systems face the challenge of having to bridge the gap whenever reference lines of the respective lanes are not measurable. This paper discusses two methods that were successfully employed in the platoon scenario of the 1997 National Automated Highway Systems Consortium Feasibility Demonstration in San Diego, USA: infrastructure-guided lane changes using an additional cross-over marker reference, and free lane changes using a yaw rate sensor for dead reckoning. Both systems achieved good passenger comfort and exhibited high reliability. Similar techniques were applied to the entrance and exit ramps of the automated highways. © 2000 Elsevier Science Ltd. All rights reserved.

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### 1. Introduction

Traffic congestion problems and driving safety issues on highways have motivated an increased amount of research into highway automation. Shladover (1995) as well as Fenton and Mayhan (1991) gave comprehensive overviews of the automated highway system (AHS). An AHS vehicle involves two basic vehicle control tasks: longitudinal control and lateral control (Hedrick, Tomizuka & Varaiya, 1994). Longitudinal control regulates vehicle speed to keep proper spacing between vehicles. Lateral control keeps the vehicle in the center of the lane (lane-keeping maneuver) and steers the vehicle into an adjacent lane (lane-change maneuver), while maintaining good passenger comfort.

One of the most important elements in the lateral guidance of an automated vehicle is the reference/sensing system. Lateral reference/sensing systems can be categor-

ized into two groups: look-ahead systems (e.g., machine-vision systems) and look-down systems (e.g., magnetic markers installed in the center of the roadway). Look-ahead systems replicate human driving behavior by measuring the lateral displacement ahead of the vehicle. A number of research groups have successfully conducted highway speed experiments with look-ahead systems using machine-vision (e.g., Dickmanns & Graefe, 1988; Jochem, Pomerleau, Kumar & Armstrong, 1995). However, machine-vision is susceptible to variations in light, or inclement weather conditions. Look-down reference systems, on the other hand, measure the lateral displacement at a location within or close to the vehicle's boundaries, typically the area directly below the front bumper. This configuration significantly improves the reliability of the sensing system, but at the expense of a shorter sensor range.

Many look-down lateral reference/sensing systems are insensitive to light and weather conditions, such as the magnetic marker system proposed by the California PATH Program (Zhang & Parsons, 1990). But these systems often have their own practical limitations. Due to the lack of forward-sensing capability, look-down reference systems impose strong design challenges on

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automated steering control because they do not provide adequate phase lead at high speeds for steering stabilization (Guldner, Tan & Patwardhan, 1996). Furthermore, the on-board sensors, such as the magnetometers for the magnet marker system, have a finite lateral sensing range, compared to the practically global lateral range of machine-vision systems. The finite lateral range of look-down reference systems usually creates an area between lanes where no vehicle-position measurement is available. The automated vehicle needs to negotiate itself through this area without reliable or direct lateral measurement. The penalty for an automated vehicle losing its direction between two lanes is extremely high. Such scenario may include the automated vehicle wandering between two lanes for a long period of time or rushing into a neighboring lane at high speed. Therefore, integrating the estimation of vehicle states and the corresponding control strategies becomes a crucial design process when look-down reference systems are used for automated lane-change maneuvers. In practice, however, such real-time estimation is a difficult proposition. Slight uncertainties in vehicle characteristics, road conditions or measurement noise may result in a sufficiently large position-estimation error, which although small in number, may cause a lane-change maneuver to fail. The difficulty involved in conducting automated lane-change maneuvers with a look-down sensing system increases dramatically when a mere 99% success rate is imposed (and such a rate is not enough). The extremely stringent robustness and smoothness requirements (i.e., how consistently and smoothly the automated lane-change can be maintained under various vehicle operating conditions), create a major design challenge for such automated vehicle maneuvers. The difficulty is further compounded when the lateral sensor range is significantly smaller than the lane width. The eventual realization of an automated steering-control system is likely either to acquire the largest available sensor range or to fuse various lateral sensing systems to improve reliability. Nevertheless, it is important to understand and to improve the limit of a limited-range lateral sensing system. The aims of this paper are to analyze and demonstrate the feasibility of conducting smooth and reliable automated lane-change maneuvers based on a range-limited look-down lateral sensing system. The success of such a demonstration also improves the practical applicability of the look-down lateral sensing system for automated vehicle control applications.

Many automated lane-change control papers focus on path-planning and trajectory tracking using ideal lateral measurements (e.g., Swaroop & Yoon, 1999; Shiller & Sundar, 1998). Most experiments reported in the literature were conducted with vision-based sensors. One noticeable exception is the automated lane-change maneuver performed by the researchers at The Ohio State University (e.g., Hatipoğlu, Redmill & Özgüner,

1998). They demonstrated automated lane-change maneuvers using a yaw-rate sensor to follow a desired open-loop yaw-rate trajectory. However, radar, a look-ahead sensor that looks in front of the vehicle for the frequency-selective stripe installed in the center of the road, was used for lane-keeping control. The issues of robustness with respect to road “noise”, sensor bias, and outside disturbances were not explicitly discussed. Chee, Tomizuka, Patwardhan & Zhang (1995), described a simulation and preliminary low-speed experimental study on lane-change maneuvers using the magnetic reference/sensing system at the California PATH Program. A Kalman filter was designed as the vehicle state estimator using yaw-rate and lateral acceleration; a trapezoidal acceleration profile was used to create the virtual desired trajectory; and sliding mode control with filter was adopted for the controller design. However, complete lane-change data was not reported in the paper. This method does not guarantee robustness at higher speeds because real-world factors such as sensor noises and vehicle parameter variations are not considered.

In this paper, two schemes for lane-change maneuvers using roadway marker reference systems are discussed: infrastructure-guided lane-change and free lane-changes. Both schemes were successfully employed with magnetic markers in the 1997 National Automated Highway Systems Consortium (NASHC) Technical Feasibility Demonstration on an 8-mile automated highway at I-15 in San Diego (Tan, Guldner, Patwardhan, Chen & Bougler 1999). Although the examples presented in this paper are based on a discrete-marker lateral system, the results are transferable to the continuous-marker system. In the infrastructure-guided lane-change scenario, additional magnetic markers (Guldner, Patwardhan, Tan & Zhang 1999) are installed between lanes to provide a reference path for automated guided-vehicles at certain locations on highways. This scheme alleviates the control and estimation problems by limiting lane-change maneuvers to specific locations; however, it also reduces the automated vehicles’ flexibility on smart highways. On the other hand, vehicle positions are estimated using on-board inertial sensors, usually a yaw-rate sensor and accelerometer, in the free lane-change scenario. Furthermore, a smooth desired trajectory is generated as a virtual reference path between lanes to implement such a scheme. Since no direct position measurement is available in this dead-reckoning approach, vehicle position errors as well as vehicle heading angles can accumulate during the course of tracking the virtual reference path. In order to remedy the effect of this possible accumulated error, immediately after the vehicle “senses” the target lane, a correcting trajectory is generated in real-time based on the new vehicle-position and heading-angle measurements. The correcting trajectory will smoothly lead the lane-change vehicle to the lane-keeping mode along the target lane. Demonstration results on the I-15

freeway show the effectiveness and consistency of both approaches.

The structure of this paper is as follows. In Section 2, the difficulties of using a look-down sensing system for automated lane-changing are investigated. Section 3 explains the requirements of the automated lane-change control with a look-down lateral reference system. Sections 4 and 5 describe the infrastructure-guided and inertial sensor-based free lane-changes, respectively. Section 6 reports the field test results and Section 7 presents the conclusion.

## 2. The look-down reference system

The fundamental difference of using look-down or look-ahead sensors for automated lane-change maneuvers is a result of the difference in the range of the lateral sensors. The look-ahead sensor typically has a larger sensor range. Lane-change and lane-keeping maneuvers become virtually identical to a trajectory-following problem when the lateral sensor sees both lanes simultaneously. The control problem becomes more complicated when the lateral sensor cannot acquire information about either lane and the vehicle must travel a certain distance without sensing any markers during a lane-change. An automated lane-change maneuver therefore involves changing between various control states based on the availability of the lateral sensing measurement. The most uncertain, and thus the most difficult phase of this maneuver occurs during the attempt to sense the new marker line in the target lane. To investigate such difficulties, one can consider a vehicle conducting a lane-change maneuver with velocity  $V$  and reaching the lateral sensor range ( $\pm y_R/2$ ) of the target lane at an arrival angle  $\theta_a$  as illustrated in Fig. 1. Note that  $y_R$  is less than the lane width as in many look-down lateral sensors.

It can be shown that a constant radius of curvature indicated in Eq. (1) minimizes the maximum lateral acceleration (min-max acceleration) that the vehicle can achieve as it approaches the centerline in the target lane without the lateral measurement being lost:

$$\begin{aligned} \min(a_{\max}) &= \frac{V^2}{\max(R_{\min})} = \frac{V^2}{y_R/(1 - \cos(\theta_a))} \\ &= 2 \frac{V^2 \sin^2(\theta_a/2)}{y_R} \approx \frac{V^2 \theta_a^2}{2y_R} \quad \text{if } \theta_a \ll 1. \end{aligned} \quad (1)$$

From Eq. (1), the required lateral acceleration for completing a lane-change, and consequently the corresponding steering control effort, increases proportionally to the inverse of the lateral sensor range as well as to both the vehicle longitudinal velocity square and arrival angle square. Therefore, the difficulty of conducting an automated lane-change maneuver grows significantly when-

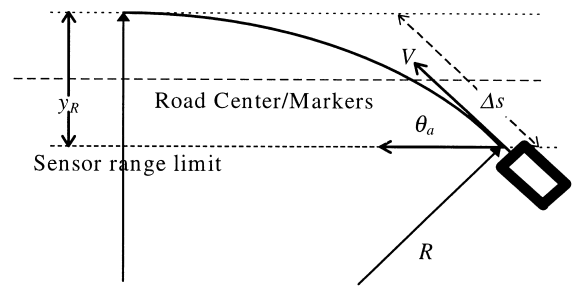


Fig. 1. Vehicle arrives at the target lane.

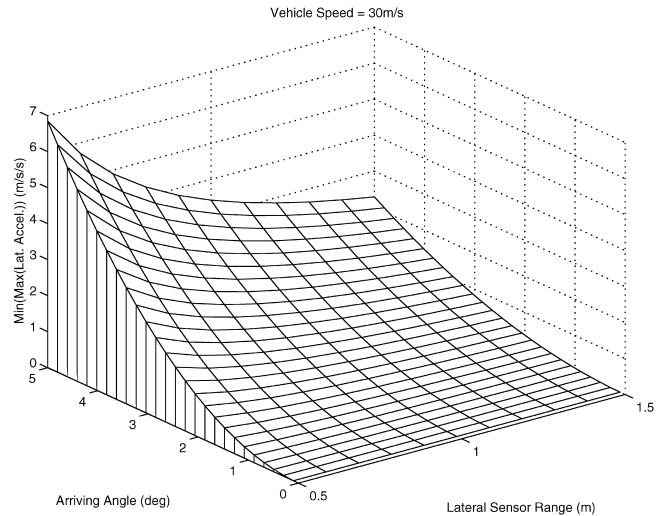


Fig. 2. Min-max lateral acceleration for lane change with limited sensor range.

ever the vehicle speed or the arrival angle increases. The elevated performance sensitivity to both vehicle speed and arrival angle is one of the major reasons that automated lane-change control systems using look-down lateral sensors demand stringent robustness and precision requirements, especially at high speeds.

For passenger vehicles using look-down lateral sensors, the typical sensor range lies between 0.6 and 2.5 m, and the automated lane-change function is generally required at any speed up to the speed limit. In order to show the sensitivity of such an automated lane change at highway speed, Fig. 2 illustrates the min-max lateral acceleration of a vehicle traveling at 30 m/s (67 mph) as functions of both sensor range  $y_R$  and arrival angle  $\theta_a$ . Since passenger comfort as well as the required tire force are mainly determined by the lateral acceleration, the arrival angle becomes the most important limitation, and an essential condition for smooth automated lane-change maneuvers at any given vehicle speed. Fig. 2 also highlights the significance of the impact from environmental uncertainties to the automated lane-change performance. For example, a change from 2 to 3° in the arrival angle due to measurement noise, results in more than double the min-max acceleration. Fig. 3 shows an

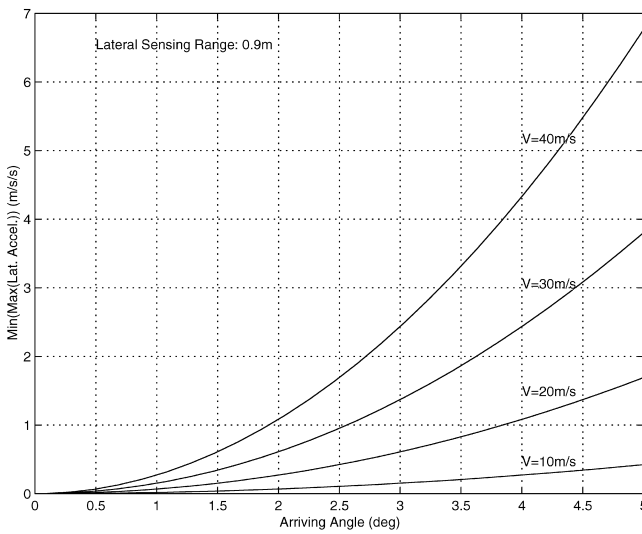


Fig. 3. Min–max lateral acceleration.

example of such min–max acceleration at different velocities with a lateral sensor range of 0.9 m. In this case, an arrival angle of less than  $2^\circ$  is required for a good lane-change transition to the target lane (maximum lateral acceleration no more than 0.1 g). In addition, the vehicle loses the lateral signal within 0.86 s ( $\Delta_s = 25.8$  m) if there is no steering correction at this arrival angle at a speed of 30 m/s. It is also important to note that the above analysis only shows the best scenario, i.e., the case when the automated vehicle follows the required curvature exactly as soon as it “senses” the target lane. Any tracking imperfection, actuating or sensing delays in the control system will effectively reduce the sensor range and thus further increase the control difficulties.

### 3. Problem statements

The purpose of automated lane-change control is to automatically steer the vehicle from the current lane to an adjacent lane. The most important requirements of such a maneuver are smoothness and robustness. Smoothness is usually defined by the maximum allowable lateral acceleration and lateral jerk. Typical numbers are, for example, 0.05 g and 0.1 g/s, respectively (Chee et al., 1995). The property of robustness is commonly referred to as the reliability of the lateral sensing system, as well as the consistency of the lane-change control system. The proximity of the look-down lateral sensor to the roadway markers generally improves the reliability of the lateral sensing, but reduces the sensor range. In cases when a limited range look-down lateral sensor is employed, the robustness of the lane-change maneuver becomes more involved. If the sensors cannot sense the markers on the adjacent lane, the automated vehicle will have to travel a certain distance during the

lane-change maneuver without direct guidance from the lateral measurement. The automated vehicle has to leave the old marker line and acquire the new marker line in a smooth fashion. It is also preferable that the resumption of the lane-keeping function in the target lane is conducted without ever leaving the sensor range. Again, this is to reduce the complexity and improve the robustness of the control system. In addition, the vehicle is required to perform these procedures consistently despite the extreme uncertainties in the vehicle operating environment. These unique operating conditions underscore the importance of smoothness and robustness for such automated maneuvers.

One can define a successful automated lane-change maneuver as follows. For a vehicle under automatic steering control with lateral sensor range of  $\pm y_R/2$  traveling at longitudinal velocity  $V$  along the road markers, a lane-change maneuver into an adjacent target lane, at lateral displacement  $y_D$  away from the current road center, is successful if the lateral displacement  $y(t)$  to the current road center and the angle  $\theta_V(t)$  between the target road center line and the vehicle traveling direction satisfy the following conditions:

$$(y_D - y(t_a)) = \text{sgn}(y_D) \frac{y_R}{2} \quad (2)$$

and

$$|\theta_V(t_a)| \leq \theta_{a\max},$$

$$\text{for some } t_a \text{ where } t_{\text{start}} < t_a \leq t_{\text{arrive}} < t_{\text{keep}}, \quad (3)$$

$$|y(t) - y_D| < \varepsilon < \frac{y_R}{2} \text{ for some } \varepsilon \text{ and } t > t_{\text{keep}}, \quad (4)$$

$$\ddot{y}(t) < a_{\max} \quad \text{and} \quad \ddot{y}(t) < J_{\max} \text{ with } t_{\text{start}} < t \leq t_{\text{keep}}, \quad (5)$$

where  $t_a$  is the time when the vehicle first comes within the lateral sensor range of the target line,  $t_{\text{start}}$  is the start time of lane-change;  $t_{\text{arrive}}$  is the time limit for entering the sensor range of the target lane, and  $t_{\text{keep}}$  the time limit for resuming normal lane-keeping functions. The vehicle's lateral displacement  $y_D$  can be viewed as the new lane-keeping equilibrium position in the target lane. Finally,  $\theta_{a\max}$ ,  $a_{\max}$ ,  $J_{\max}$  are the maximum allowable arrival angle, maximum lateral acceleration and maximum lateral jerk, respectively. The maximum allowable arrival angle  $\theta_{a\max}$  is bounded by the extreme trajectory-tracking capability of the lane-keeping control system, with which the automated vehicle can still “catch” the new marker line and change to the lane-keeping function with an acceptable smoothness. The smaller  $\theta_{a\max}$  is, the more precision is required for both the dead-reckoning operation and lane-tracking control. In that sense, the angle  $\theta_{a\max}$  includes both the nominal arrival angle and its maximum allowable deviation.

Generally speaking, Eq. (2) guarantees that the vehicle reaches the adjacent target lane; (3) provides the

necessary “small arrival angle” condition for a smooth transition as explained in Section 2; (4) requires an eventual transition to the lane-keeping control; and (5) specifies the requirements for the passenger comfort during the entire lane-change maneuver. Eq. (5) can also be divided into two sub-conditions in practice: one set of bounds for  $t_{start} < t \leq t_{arrive}$ , and another one for  $t_{arrive} < t \leq t_{keep}$ . The first set, the maximum lateral acceleration and jerk, relates to the lane-change trajectory, while the second set provides limits for the worst “lane-catching” situation. Eqs. (3) and (5) specify the requirements for smooth trajectory planning, accurate dead reckoning and a strong lane-keeping (tracking) controller.

Three basic methods can be devised for conducting automated lane-change maneuvers using range limited lateral sensors: open-loop lane-changing, infrastructure-guided lane-changing, and free lane-changing using inertial sensors. The difference between these methods lies with the different choices of guiding technique used during the period when no direct road measurement is available between lanes. The open-loop method uses prescribed steering command; the infrastructure-guided method uses additional pre-installed road markers between lanes at predetermined locations; and the free-lane change method employs dead reckoning with inertial sensors that estimate the vehicle’s lateral states. Except when the “gap” between two lanes is very small, the open-loop lane-change method has proved to be the least robust method because of its extreme sensitivity to vehicle and road uncertainties. Therefore, the two approaches that satisfy the above lane-change requirements are infrastructure-guided lane-changing and free lane-changing using inertial sensors. These two methods are investigated in detail in Sections 4 and 5, respectively.

Although a good lane-keeping controller is essential for any robust lane change maneuver, its design is not within the scope of this paper; only the related controller requirements will be discussed hereafter. Refer to Tan et al. (1999) for the corresponding controller design that achieved a lane-keeping accuracy of better than 10 cm at speeds up to 130 km/h (80 mph), that also maintained a 0.5 g lateral acceleration on sharp curves.

#### 4. Infrastructure-guided lane changing

In the case of infrastructure-guided lane-changing, a new line of markers is installed in between two lanes of the roadway at locations specifically designated for lane-changing (see Fig. 4 for an illustration of this). This additional marker line is designed to guide the automated vehicle from the traveling lane to the adjacent target lane. After receiving a lane-change command, the automated vehicle will start a lane-change maneuver at a proper location in front of the next available guided

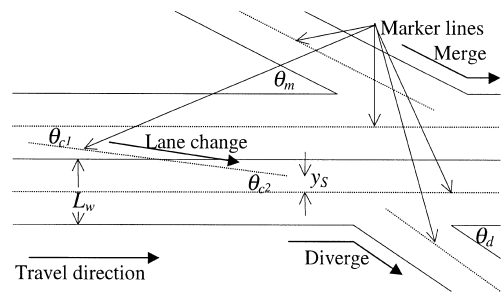


Fig. 4. Infrastructure-guided maneuvers.

marker line by following a prescribed trajectory offset from the current marker line. A priori information about the exact location of this guide line and its relative orientation with respect to the traveling lane should either be transmitted to the vehicle or stored in the vehicle’s memory before the lane-change maneuver begins. Roadside transponders or marker coding (Guldner et al., 1999) provide a means for such information transmission. Although it seems straightforward to provide an offset trajectory that connects the two marker lines, sensor limitation or field interference often requires a certain minimum spacing between marker lines. For instance, two adjacent magnetic marker lines should not be installed too close to each other to avoid the extra complication of field interference. When the vehicle can simultaneously “sense” both marker lines during transition from one to the other, the automated lane-change maneuver essentially performs a normal lane-keeping function that follows a continuous trajectory appropriately offset from the closest marker line. If  $y_s$ , the distance between the two marker lines, is slightly greater than the sensor range  $y_R$ , it may be feasible to use an open-loop steering command to steer the vehicle across the marker gap between the two marker lines without any additional sensors. Otherwise, dead-reckoning with the inertial sensor, as described in Section 5, would be more appropriate for added robustness.

An infrastructure-guided lane-change usually starts while the automated vehicle is under normal lane-keeping function along one of the main lanes at a certain distance before the guide line. To smoothly switch between marker lines, the automated lane-change maneuver is composed of the following natural sequence of controller states as shown in Fig. 5:

- (1) *Lane-splitting*: The automated vehicle follows a prescribed trajectory offset from the markers until it leaves the sensor range of the main marker line,
- (2) *Open-loop/dead-reckoning*: The automatic vehicle uses either a prescribed open-loop steering command or follows a predetermined trajectory, based on the dead-reckoning estimation of lateral displacement until it sees the connecting guide line,

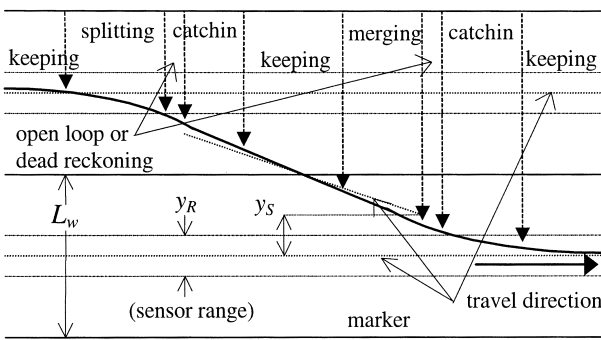


Fig. 5. Infrastructure-guided lane change.

- (3) *Lane-catching*: The automatic vehicle determines and follows the transitional trajectory determined by the initial conditions of the vehicle when it first encountered the new line to smoothly align itself to the guide line,
- (4) *Lane-keeping*: Once it has latched on to the guided marker line, the automatic steering control starts the normal lane-keeping control function along this connecting guide line,
- (5) *Lane-merging*: The automated vehicle follows a prescribed trajectory offset from the marker line to properly position its approach angle to the target marker line,
- (6) *Open-loop/dead-reckoning*: After reading the last marker of the guide line, the automatic vehicle either uses a predetermined open-loop steering command or follows a virtual trajectory based on dead reckoning to search for the target lane,
- (7) *Lane-catching*: Once the lateral sensor reads the markers from the target lane, the automatic algorithm determines and follows a trajectory that then smoothly transfers the vehicle to the normal lane-keeping function in the target lane, and
- (8) *Lane-keeping*: The vehicle resumes normal lane-keeping control along the marker line of the target lane.

For cases of wider-ranged sensors ( $y_R > y_S$ ), the open-loop/dead-reckoning control (controller states 2 and 6) can be eliminated from the control sequence and the marker measurements are available for all controller states. A continuous trajectory that links these three marker lines can be achieved.

Fig. 4 also shows that freeway entry (merge) and exit (diverge) maneuvers can be viewed as parts of the infrastructure-guided lane-change maneuver. Entering the freeway is analogous to the part of the infrastructure-guided lane-change from the guide line to the target lane (controller states 4, 5, 6, 7, 8); whereas exiting the freeway is similar to moving from the current lane to the guide line (controller states 1, 2, 3, 4). The difference lies in the design of the virtual trajectory, which is usually a function of roadway geometry and initial conditions.

An infrastructure-guided lane-change maneuver requires the vehicle to change from following one line of road markers to following another line. A simple trajectory-tracking steering controller is therefore not adequate to smoothly complete such an automated maneuver. In addition, methods that plan the trajectory in real-time, bridge the dead zone between two marker lines, as well as integrate the planning and control together, should be included in such lane-change control design. The proposed design of the automated infrastructure-guided lane-change maneuver involves the development of the following four components:

- (1) controller state machine;
- (2) trajectory planning;
- (3) open-loop steering command or dead-reckoning estimation; and
- (4) lane-keeping controller.

The controller state machine determines the proper changes between controller states based on current and past inputs from the lateral sensors; the travel plan and the driver demands; as well as the a priori information about the lane-change (or entry and exit) guide lines. Trajectory planning calculates the appropriate offsets with respect to the available lateral measurements that either smoothly guide the vehicle away from the current marker line or align the vehicle to the new marker line in time. The lane-keeping controller is the feedback mechanism that tracks either the normal lane markers or the planned trajectory with sufficient accuracy, smoothness and robustness. Open-loop steering command, often calculated based on the filtered past steering commands and the known road geometry, is a simple and effective means of steering the vehicle when the gap between marker lines is sufficiently small. Dead reckoning with inertial sensor-support, as will be discussed in the next section, is preferable in practice when this gap is large or when the road and vehicle uncertainties are high. The lane-catching trajectory also improves the reliability of such maneuvers since it is designed to smoothly correct the transitioning error accumulated during the gap.

Three trajectories need to be determined during an infrastructure-guided lane-change maneuver: lane splitting, lane merging and lane catching. Although fifth-order polynomials provide a smoother trajectory, third-order polynomials were chosen for field-testing because of their simpler real-time computation and faster initial correction during lane-catching. Since the guided lane-change maneuvers are performed based on marker locations, the trajectories are defined as functions of the longitudinal positions as shown in Eqs. (6) and (7). The vehicle tracks the desired trajectory ( $y = y_d(x)$ ) instead of the road center ( $y = 0$ ). The desired trajectory is described as:

$$y_d(x) = a_3x^3 + a_2x^2 + a_1x + a_0 \quad (6)$$

Table 1  
Trajectory planning for infrastructure-guided lane change

	$y_d(0)$	$\dot{y}_d(0)$	$y_d(x_f)$	$\dot{y}_d(x_f)$
Lane splitting	0	0	$-y_s$	$\theta_{c1} + \psi$
Lane merging	0	0	$y_s$	$-\theta_{c2} - \psi$
Lane catching	$y(t_a)$	$\dot{\theta}_a$	0	0

with

$$a_0 = y_d(0),$$

$$a_1 = \dot{y}_d(0) = \frac{dy_d}{dx}(0),$$

$$a_2 = -\frac{2(y_d(x_f) - y_d(0))}{x_f^3} + \frac{\dot{y}_d(x_f) + \dot{y}_d(0)}{x_f^2},$$

$$a_3 = \frac{3(y_d(x_f) - y_d(0))}{x_f^2} - \frac{\dot{y}_d(x_f) + 2\dot{y}_d(0)}{x_f}. \quad (7)$$

For simplicity, the longitudinal position  $x$  starts at 0 and lines up with the corresponding starting marker location for the proper maneuver. Parameter  $x_f$  defines the length of the trajectory. Table 1 shows a typical application of Eq. (6) to lane-splitting, -merging and -catching scenarios. The length of the trajectory chosen can be between 20 and 40 m depending on the road geometry (e.g.,  $\theta_{c1}$  and  $\theta_{c2}$ ), sensor range and vehicle speed. As in Eq. (3),  $\psi$  is an additional safety factor to satisfy the small approaching angle requirement. The lane-catching trajectory depends on the initial states of the vehicle when it first encounters the marker line, as well as the sensor's range. In practice, the trajectory planning does not start until several markers are read to filter out the measurement noises and provide better estimates for the initial states. Fifth-order polynomials can also be implemented in a similar fashion where the initial jerk can be explicitly specified (e.g.,  $\ddot{y}_d(0) = \ddot{y}_d(x_f) = 0$ ). As always, a good lane-keeping controller is crucial since the controller is used to track any desired trajectory of lateral acceleration ( $V^2/(\partial y_d/\partial x)$ ).

## 5. Automated free lane changing

Although the infrastructure-guided method reduces the uncertainties during the automated lane change, limited flexibility is its main disadvantage. The free lane change, on the other hand, should impose as few limitations as possible. An automated vehicle should be able to conduct free lane changes at any area that is designated for lane changing even without detailed road information. The major difficulty in performing automated free lane changes in practice is the high performance sensitivity with respect to sensor noises, vehicle/road parameters variations and any environmental disturbances. In fact,

to design a control system that can successfully conduct thousands of consecutive automated lane changes at various locations demands a special effort.

Several methods have been proposed for free lane-change steering control when the lateral sensor senses neither lane during part of the lane-change period. The control methodologies used during the “dead zone” area generally fall into two categories: trajectory following based on state estimation using inertial sensors (Chee et al., 1995), and inertial-sensor signal-following based on a reference generated by the open-loop trajectory (Hatipoğlu et al., 1998). Both methods do not explicitly address concerns about robustness and reliability over the wide range, high noise and large variability of the vehicle's operating conditions. Both methods require knowledge of vehicles parameters or exact geometric road information and clean sensor signals for a successful maneuver.

To improve the reliability of the automated free lane-change maneuver, a free lane-change control algorithm was proposed in this paper. It consists of the following four cooperative control schemes:

- (1) a lateral displacement observer/estimator using a yaw-rate sensor (and/or accelerometer) that results in bounded estimation error;
- (2) an adaptive lane-change and lane-catching trajectory-planning scheme that guarantees a smooth final arrival at the target marker line;
- (3) a robust and high damping lane-keeping control algorithm that is capable of tracking the desired trajectory under the worst case scenario; and
- (4) a state machine that quickly coordinates the above schemes and determines the proper vehicle operational-state based on sensor signals, available road information and maneuver demands.

Because a lateral accelerometer is usually noisier and more sensitive to the sensor location, a yaw-rate sensor is chosen to provide the input to the lateral displacement estimator. The purpose of such an estimator is to determine the lateral displacement using the yaw-rate measurement when the lateral sensors detect no markers between lanes. To reduce the sensitivity to dynamic vehicle variations, a more reliable kinematic relationship between lateral displacement and yaw-rate is used for the design. At small angles (both vehicle-traveling and tire-slip angles), the vehicle's lateral displacement  $y$  can be written kinematically as

$$\ddot{y} = V\omega \quad (8)$$

with  $\omega$  the vehicle yaw rate. According to Eq. (8), lateral displacement is basically a double integral of the yaw-rate measurement. Therefore the computation of lateral displacement using yaw-rate is extremely sensitive to bias. Three major sources of bias exist: (1) the yaw-rate

sensor bias or drifting; (2) the yaw-rate contribution from the road’s curvature and from the road’s super-elevation; and (3) a slight variation in the estimate of the initial conditions as the vehicle leaves the marker line. Eq. (9) describes a “kinematic” estimate of  $\hat{y}$  that includes the contributions from bias and the initial conditions, where  $y_0, \theta_0$  and  $\omega_0$  are the initial conditions or biases in lateral displacement, vehicle-angle and yaw-rate, respectively,

$$\hat{y} = \hat{y}_0 + V\hat{\theta}_0 t + \frac{1}{2}V\hat{\omega}_0 t^2 + V \iint \omega dt. \quad (9)$$

The basic procedure of the observer/estimator is to estimate the initial conditions and bias ( $y_0, \theta_0$  and  $\omega_0$ ) in Eq. (9) first, using the lateral measurements when they are available. Under the assumption that these values remain unchanged (or change very little) during the short “gap” period without position readings, Eq. (9) is used for the dead-reckoning computation of  $\hat{y}$ , taking the final estimates of these initial conditions as constants as the vehicle exits the sensor range. In practice, the discrepancy between these initial condition estimates have been shown to be the major contributor to error in the lateral displacement estimate. Furthermore, since the road geometry is included in the estimate, the free lane-change maneuver can be performed without curvature information as long as it is not conducted during any changes in road curvature.

In order to use Eq. (9) as the displacement estimator during the short “gap” period, the following initial conditions:  $y_0, \theta_0$  and  $\omega_0$ , should be identified. Among them,  $\omega_0$  contributes the most toward the estimation error. The vehicle traveling at angle  $\theta_V$  can be described as:

$$\dot{\theta}_V = \omega_V - \omega_R, \quad (10)$$

where  $\omega_V$  is the true vehicle yaw-rate,  $\omega_R$  is the yaw-rate corresponding to the road geometry and vehicle speed. The vehicle angle estimator  $\hat{\theta}_V$  can be written as

$$\dot{\hat{\theta}}_V = \omega_M + K_e(\bar{\theta}_V - \hat{\theta}_V), \quad (11)$$

with

$$\omega_M = \omega_V + \omega_N, \quad \text{and} \quad \bar{\theta}_V = \theta_V + \theta_n,$$

where  $\omega_N$  is the measurement noise (white noise) combined with the bias (slow varying) of yaw-rate sensor,  $\bar{\theta}_V$  is the computed value of  $\theta_V$  (e.g., based on displacement measurements),  $\theta_n$  is the computational error, and  $K_e$  is the observer feedback gain. The estimate of  $\omega_0$  can be constructed from the following equation by combining Eqs. (10) and (11):

$$K_e(\bar{\theta}_V - \hat{\theta}_V) = \frac{-K_e}{s + K_e}(\omega_R + \omega_N) + \frac{K_e s}{s + K_e}\theta_n. \quad (12)$$

It is interesting to notice that the right-hand side of Eq. (12) consists of a first-order low-pass filtered  $(\omega_R + \omega_N)$  and a first-order high-pass filtered  $\theta_n$ . Both filters possess

the same corner frequency at  $K_e$ . Since  $(\omega_R + \omega_N)$  is exactly the yaw-rate “bias” (road contribution and sensor bias) that is used in Eq. (9) after the vehicle leaves the lateral sensor’s range, a low-pass filtered  $K_e(\bar{\theta}_V - \hat{\theta}_V)$  as in Eq. (13) would provide a good estimate for the yaw-rate bias as long as the high-frequency portion of the computational noise (from  $\theta_n$ ) is removed.

$$\hat{\omega}_0 = -G_{lp}(s)K_e(\bar{\theta}_V - \hat{\theta}_V). \quad (13)$$

To effectively reduce the impact from  $\theta_n$ , the bandwidth of this additional low-pass filter ( $G_{lp}(s)$ ) is chosen to be between  $K_e/5$  and  $K_e/10$ . The delay from this low-pass filter creates the only restriction of such automated lane-changing: the lane changes should not be initiated right after a change in the road’s curvature until a time span corresponding to the time constant of this low-pass filter is passed. The same technique can also be applied to the kinematic relationship between  $y$  and  $\theta_V$  to obtain the estimate  $\hat{\theta}_0$  when the direct calculation of vehicle angle is not accurate enough. The estimate  $\hat{y}_0$  is usually obtained using the last available displacement measurement. In order to further increase the robustness in practice, additional filters may be added to provide bounds for estimates or to remove specific noises (such as spikes) in the measurements.

Only two controller states are needed for the free lane-change scenario: lane-change and lane-catching, as shown in Fig. 6. Although the lane-change state can be subdivided into lane-splitting (using the lateral measurement) and yaw-rate supported lane-change (using the lateral estimate), the trajectory-planning is identical. The difference lies in which lateral displacement (measurement or estimate) is selected for the trajectory tracking control.

Trajectory-planning is a crucial component in completing the automated free lane-change maneuver. Two trajectories need to be designed:

- (1) *lane-change trajectory*: the trajectory that the vehicle follows to leave the traveling lane (based on marker measurement offset) and perform the lane-change maneuver (based on lateral displacement estimate)

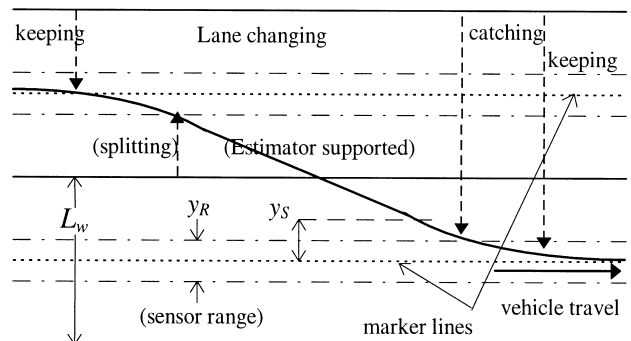


Fig. 6. Automated free lane change.



Table 2  
Trajectory-planning for free lane change

	$y_d(0)$	$\dot{y}_d(0)$	$y_d(x_f)$	$\dot{y}_d(x_f)$
Lane change	0	0	$\pm L_w$	$\pm \psi$
Lane catching	$y(t_a)$	$\theta_a$	0	0

- until the lateral sensor receives the first marker signal from the target lane;
- (2) *lane-catching trajectory*: the trajectory that smoothly leads the vehicle to align itself to the new marker line once it senses the first marker.

Both third and fifth-order polynomials as described in Section 4 can be used for the lane-change/catching trajectory. Table 2 shows the coefficients of a typical application of Eq. (6) to lane-changing, and lane-catching scenarios, with  $L_w$  the lane width and  $\psi$  the designated final approaching angle. The length of the trajectory planning,  $x_f$ , is usually adaptive to vehicle speed so that the time of dead reckoning is limited to 3–5 s. However for simplicity, a fixed number between 150 and 200 m for lane changes and 20 and 40 m for lane catching is also applicable. Furthermore, the lane-change trajectory modifies itself if the vehicle does not reach the target lane after a prescribed time interval.

Although the lane-keeping controller is not the central issue discussed in this paper, it is essential for the robustness of the whole lane change maneuver. Not only it is the final safeguard of this automated maneuver, but the strength of the lane-keeping controller also determines the allowable maximum estimator errors. The controller has to bring the vehicle back to the lane-keeping function even at the largest possible arrival angle created by the estimator errors.

6. Field testing

Both infrastructure-guided lane-changes and free lane-changes using magnetic marker reference systems were successfully demonstrated at highway speeds by PATH in the 1997 NAHSC Technical Feasibility Demonstration on an eight-mile automated highway at I-15 in San Diego, USA. The demonstration vehicles were standard Buick LeSabres with add-on devices for automated steering control, including magnetic sensors for measuring the vehicle’s lateral position, an electronically controlled steering actuator and a Pentium computer (Tan et al., 1999). Magnetic markers were buried along the centerlines of both lanes at 1.2 m intervals. In the infrastructure-guided lane-change scenario, additional straight-line magnetic markers are installed between lanes (with  $y_s = 0.9$  m to avoid magnetic interference,

and  $\theta_c = 1^\circ$ ) to provide a reference marker line at several locations on the highway. By specifically alternating the polarities of the magnetic markers, the markers also transmit roadway characteristics such as the upcoming road geometry, mileposts, entrances, exits and the exact locations of the infrastructure-guided marker lines to the vehicle (Guldner et al., 1999). By counting the magnet numbers, the vehicle knows the relative distance to the nearest guided line or to the designated lane-change area.

Figs. 7(a) and (b) illustrate the field test results of automated free lane-change maneuvers on the I-15 test track. Two consecutive free lane changes were recorded: the first one ( $t_{start} = 12.5$  s) was a right lane change at 105 km/h (65 mph) and the second one ( $t_{start} = 41$  s) a left lane change at 120 km/h (75 mph). Fig. 7(a) compares

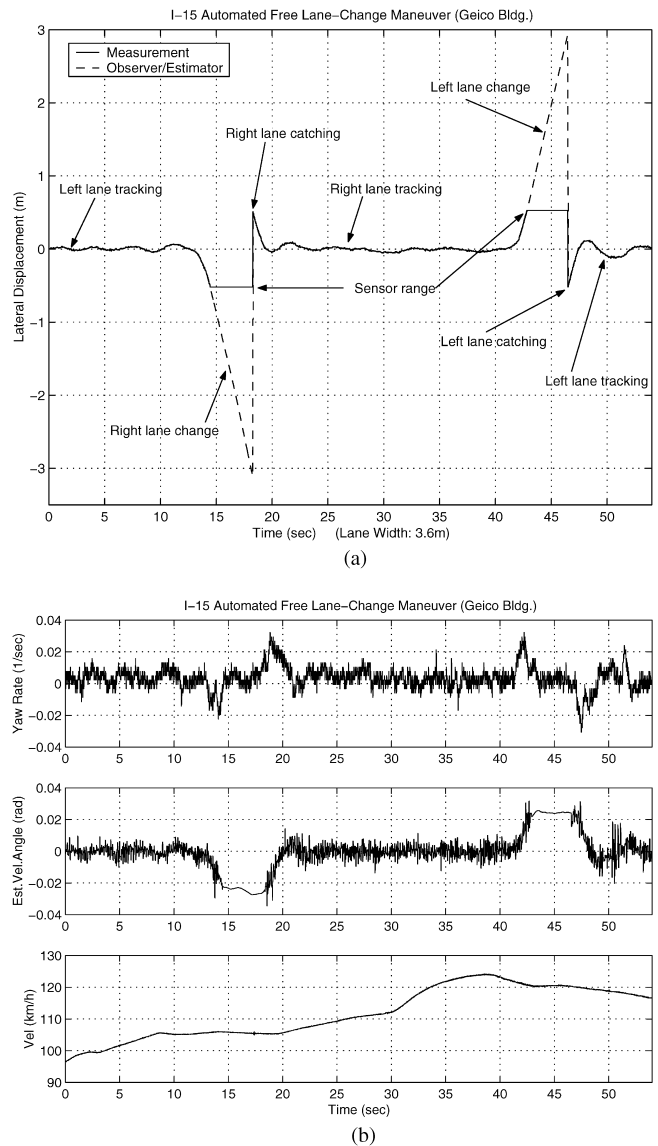


Fig. 7. Automated free lane changes on I-15: (a) displacement measurement & estimate and (b) yaw rate, angle estimate, velocity.

the lateral displacement measurement with its estimation. The vehicle first followed a desired lane-change trajectory (third-order polynomials for this case) guided by the magnetic measurements until it left the sensor range at  $-0.52$  m (left side of the vehicle). The vehicle continued to track the same desired trajectory using the estimated displacement instead of the measurement until the sensor saw the first magnet on the target lane  $0.53$  m (right side of the vehicle) away from the new lane center. At this time, the estimator reading was  $-3.11$  m ( $2.93$  m for the second lane change). The errors of these two estimates were within  $0.20$  m since the correct estimation (at the first marker reading) should be about  $\pm 3.1$  m (the lane width,  $3.6$  m, minus the sensor range,  $\sim 0.5$  m). The vehicle then switched to the lane catching function with a new desired trajectory calculated by third-order polynomials whose coefficients are determined by the initial catching condition. Finally, the vehicle resumed the lane-keeping function after finishing lane catching. Fig. 7(b) also shows the yaw-rate sensor measurement and the estimated vehicle angle with respect to the road. The estimator's performance can be highlighted by the fact that a  $0.2$  m error on the lateral displacement estimate at the first reading of the new marker line can be generated either by an error of  $0.0015$  rad/s on the yaw-rate initial bias estimate or a  $0.0023$  radian error on the initial departure angle (by using Eq. (9) with  $V = 30$  m/s and  $t = 3$  s). Notice that these are very small numbers in practice. With the high-gain lane-keeping controller, over 400 consecutive automated free lane-change maneuvers were successfully performed in 1997 at various highway speeds at different locations on I-15 without a single failure. The estimator errors were almost always less than  $0.35$  m for when the vehicle first senses the target lane at about  $3.1$  (i.e.,  $3.6-0.5$ ) m away from the initial lane center.

Figs. 8(a) and (b) demonstrate a 4 min test run with both types of automated lane changes on I-15. The steering control was automated but the driver commanded the brake and throttle to test robustness with respect to various speeds. Five consecutive automated lane changes (in the sequence of right, left, right, left and right) were performed during this test run: two infrastructure guided lane-changes (first and fourth) and three free lane-changes (second, third and fifth) as indicated by the lateral displacement in Fig. 8(a). The sensor range of the test vehicle is about  $\pm 0.5$  m with the sign convention that positive readings indicate that magnet is on the right-hand side of the vehicle. Any measurement in Fig. 8(a) with an absolute value greater than  $0.5$  m is the result of the lateral position estimation. The reappearance of the magnetic line on the opposite side of the vehicle after leaving the original line of markers creates the jumps in the figure. The sequence of state transitions during the infrastructure-guided lane-change can also be observed in Fig. 8(a). Lane splitting ended and open loop started

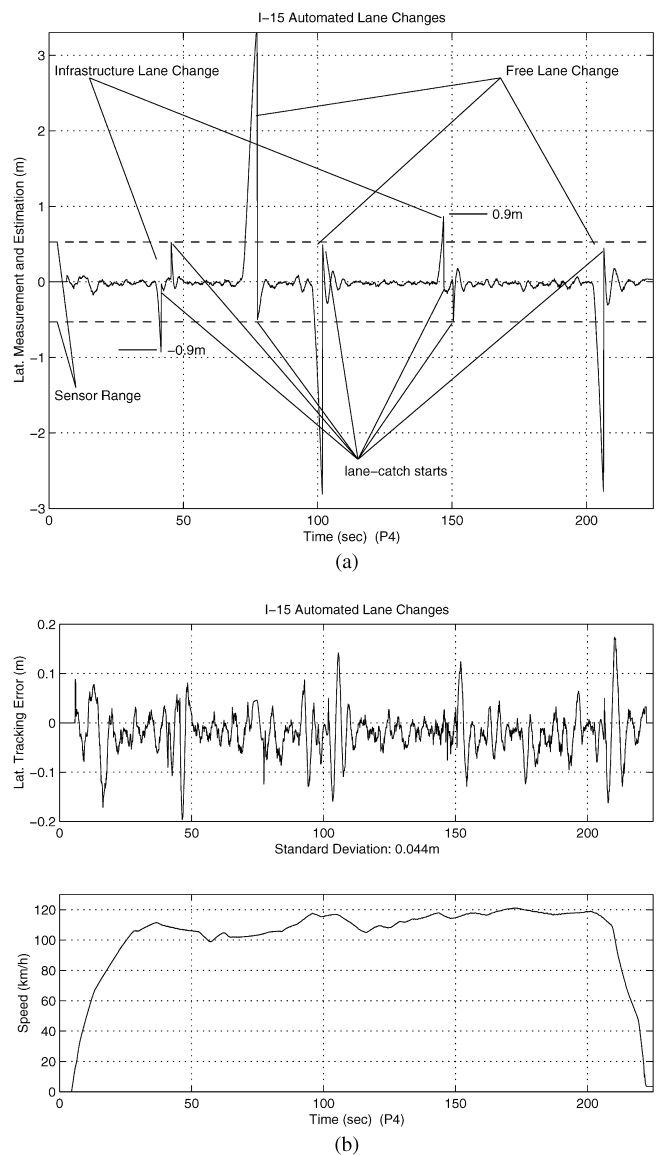


Fig. 8. Automated lane changes on I-15: (a) lat. displacement and (b) tracking error and speed.

when the vehicle crossed over the sensor range at about  $\pm 0.5$  m. The open-loop command brought the vehicle to the connecting guided marker lines at  $\pm 0.9$  m as indicated by the estimated lateral displacement. The vehicle then caught the connecting marker line head-on with the first lateral reading within  $0.1$  m. Following this guided marker line, the vehicle again went through lane-catching, -keeping, -merging, and open-loop states, then left the connecting marker line. Once again, it caught the first marker on the target lane at about  $\pm 0.5$  m away from the new marker line, and finally resumed lane-keeping functions after finishing the lane catching. Again, the three free lane-change maneuvers arrived at the target marker line with estimator errors of less than  $0.3$  m. Fig. 8(b) illustrates the lateral tracking error, i.e., the error

between the desired trajectory and either the lateral measurement or its estimate when the measurement was not available. The maximum tracking error was less than 0.2 m during the entire test run, (errors that are more than 0.1 m usually occurred during the lane-catching state), and the overall standard deviation of tracking error was slightly less than 4.5 cm. This tracking accuracy underscored the strong performance requirement for the lane-keeping (tracking) controller. Finally, the yaw-rate measurement, despite its noise, indicates good passenger comfort was also achieved.

## 7. Conclusion

The major problem of conducting the automated lane-change maneuvers based on a look-down lateral reference/sensing system lies in its limited sensor range, especially when the lateral sensor cannot “sense” any road markers during part of the maneuver. The most important requirements of such maneuver are the smoothness of the transition and reliability under various vehicle conditions. Two methods for solving this difficult problem have been reported in this paper. The infrastructure-guided lane-change takes the advantage of an additional marker line strategically installed on the freeway to assist lane-change maneuvers. Although the infrastructure-guided method reduces the flexibility of the smart highway, it is a natural method to apply to entering and exiting highways, as well as lane-changing around difficult traffic areas. The free lane change maneuver, on the other hand, uses an on-board inertial sensor during lane changes to perform dead-reckoning estimations. Free lane changing is sensitive to both sensor noise and vehicle/road parameters variations. A cooperative control scheme that consists of adaptive trajectory-planning, geometric displacement estimation, and a strong tracking controller is proposed for automated free lane changing in this paper. Both schemes were successfully field-tested and both achieved good passenger comfort and exhibited high reliability. The successful results substantiate the feasibility of conducting smooth and reliable automated lane-change maneuvers based on look-down lateral sensing systems.

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