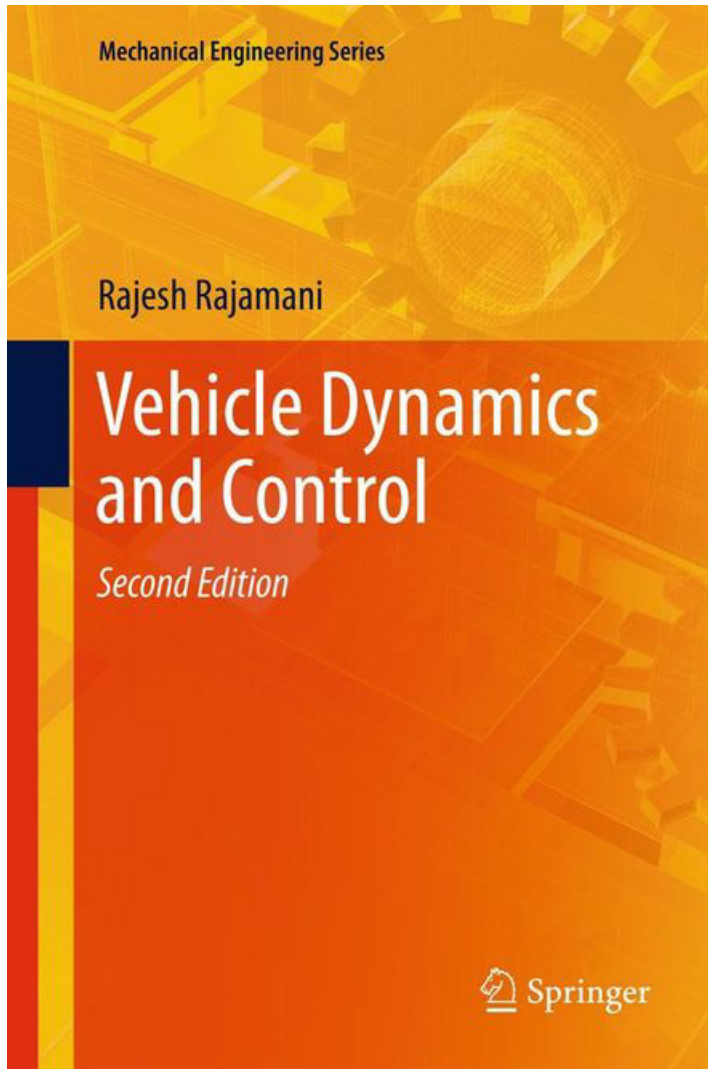


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Chapter 2

LATERAL VEHICLE DYNAMICS

The first section in this chapter provides a review of several types of lateral control systems that are currently under development by automotive manufacturers and researchers. The subsequent sections in the chapter study kinematic and dynamic models for lateral vehicle motion. Control system design for lateral vehicle applications is studied later in Chapter 3.

2.1 LATERAL SYSTEMS UNDER COMMERCIAL DEVELOPMENT

Lane departures are the number one cause of fatal accidents in the United States, and account for more than 39% of crash-related fatalities. Reports by the National Highway Transportation Safety Administration (NHTSA) state that as many as 1,575,000 accidents annually are caused by distracted drivers - a large percentage of which can be attributed to unintended lane departures. Lane departures are also identified by NHTSA as a major cause of rollover incidents involving sport utility vehicles (SUVs) and light trucks (<http://www.nhtsa.gov>).

Three types of lateral systems have been developed in the automotive industry that address lane departure accidents: lane departure warning systems (LDWS), lane keeping systems (LKS) and yaw stability control systems. A significant amount of research is also being conducted by university researchers on these types of systems.

2.1.1 Lane departure warning

A lane departure warning (LDW) system is a system that monitors the vehicle's position with respect to the lane and provides warning if the vehicle is about to leave the lane. An example of a commercial LDW system under development is the AutoVue LDW system by Iteris, Inc. shown in [Figure 2-1](#).

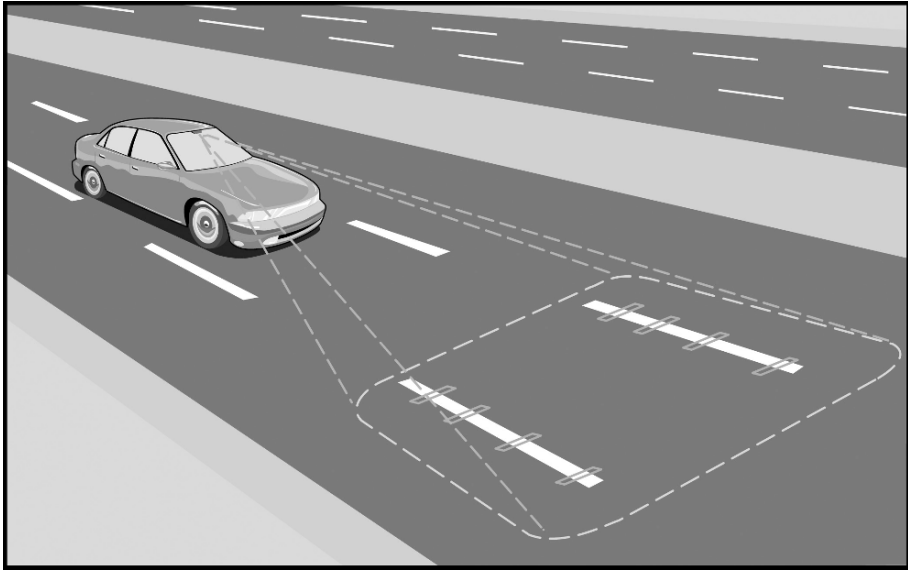


Figure 2-1. LDW system based on lane markings¹

The AutoVue device is a small, integrated unit consisting of a camera, onboard computer and software that attaches to the windshield, dashboard or overhead. The system is programmed to recognize the difference between the road and lane markings. The unit's camera tracks visible lane markings and feeds the information into the unit's computer, which combines this data with the vehicle's speed. Using image recognition software and proprietary algorithms, the computer can predict when a vehicle begins to drift towards an unintended lane change. When this occurs, the unit automatically emits the commonly known rumble strip sound, alerting the driver to make a correction.

AutoVue is publicized as working effectively both during day and night, and in most weather conditions where the lane markings are visible. By

¹ Figure courtesy of Iteris, Inc.

simply using the turn signal, a driver indicates to the system that a planned lane departure is intended and the alarm does not sound.

Lane departure warning systems made by Iteris are now in use on trucks manufactured by Mercedes and Freightliner. Iteris' chief competitor, *AssistWare*, has also had success in the heavy truck market: their *SafeTrac* system is now available as a factory option on *Kenworth* trucks and via direct sales to commercial fleets (<http://www.assistware.com>).

2.1.2 Lane keeping systems

A lane-keeping system automatically controls the steering to keep the vehicle in its lane and also follow the lane as it curves around. Over the last ten years, several research groups at universities have developed and demonstrated lane keeping systems. Researchers at California PATH demonstrated a lane keeping system based on the use of cylindrical magnets embedded at regular intervals in the center of the highway lane. The magnetic field from the embedded permanent magnets was used for lateral position measurement of the vehicle (Guldner, et. al., 1996). Research groups at Berkeley (Taylor, et. al., 1999) and at Carnegie Mellon (Thorpe, et. al., 1998) have developed lateral position measurement systems using vision cameras and demonstrated lateral control systems using vision based measurement. Researchers at the University of Minnesota have developed lane departure warning and lane keeping systems based on the use of differential GPS for lateral position measurements (Donath, et. al., 1997).

Systems are also under development by several automotive manufacturers, including Nissan. A lane-keeping system called LKS, which has recently been introduced in Japan on Nissan's *Cima* model, offers automatic steering in parallel with the driver (<http://ivsource.net>). Seeking to strike a balance between system complexity and driver responsibility, the system is targeted at 'monotonous driving' situations. The system operates only on 'straight-ish' roads (a minimum radius will eventually be specified) and above a minimum defined speed. Nissan's premise is that drivers feel tired after long hours of continuous expressway driving as a result of having to constantly steer their vehicles slightly to keep them in their lane. The LKS attempts to reduce such fatigue by improving stability on the straight highway road. But the driver must remain engaged in actively steering the vehicle – if he/she does not, the LKS gradually reduces its degree of assistance. The practical result is that you can't "tune out" and expect the car to drive for you. Nissan's argument is that this approach achieves the difficult balance between providing driver assistance while maintaining driver responsibility. The low level of steering force added by the control isn't enough to interfere with the driver's maneuvers.

The system uses a single CCD camera to recognize the lane demarkation, a steering actuator to steer the front wheels, and an electronic control unit. The camera estimates the road geometry and the host vehicle's position in the lane. Based on this information, along with vehicle velocity and steering wheel angle, the control unit calculates the steering torque needed to keep within the lane.

Nissan is also developing a LDW system called its Lane Departure Avoidance (LDA) system (<http://ivssource.net>). The LDA system aims to reduce road departure crashes by delaying a driver's deviation from the lane in addition to providing warning through audio signals and steering wheel vibrations. Nissan's LDA creates a lateral "buffer" for the driver, and kicks into action to automatically steer if the vehicle starts to depart the lane. But, unlike a true co-pilot, the system won't continue to handle the steering job – with haptic feedback in the steering wheel, the driver is alerted to the system activation and is expected to re-assert safe control by himself or herself. The automatic steering assist is steadily reduced over a period of several seconds. So, a road departure crash is still possible, but is expected to be less likely unless the driver is seriously incapacitated.

LDA is accomplished using the same basic components of LKS: a camera, a steering actuator, an electronic control unit, and a buzzer or other warning device.

2.1.3 Yaw stability control systems

Vehicle stability control systems that prevent vehicles from spinning and drifting out have been developed and recently commercialized by several automotive manufacturers. Such stability control systems are also often referred to as yaw control systems or electronic stability control systems.

Figure 2-2 schematically shows the function of a yaw control system. In this figure, the lower curve shows the trajectory that the vehicle would follow in response to a steering input from the driver if the road were dry and had a high tire-road friction coefficient. In this case the high friction coefficient is able to provide the lateral force required by the vehicle to negotiate the curved road. If the coefficient of friction were small or if the vehicle speed were too high, then the vehicle would be unable to follow the nominal motion required by the driver – it would instead travel on a trajectory of larger radius (smaller curvature), as shown in the upper curve of Figure 2-2. The function of the yaw control system is to restore the yaw velocity of the vehicle as much as possible to the nominal motion expected by the driver. If the friction coefficient is very small, it might not be possible to entirely achieve the nominal yaw rate motion that would be achieved by

the driver on a high friction coefficient road surface. In this case, the yaw control system would partially succeed by making the vehicle's yaw rate closer to the expected nominal yaw rate, as shown by the middle curve in [Figure 2-2](#).

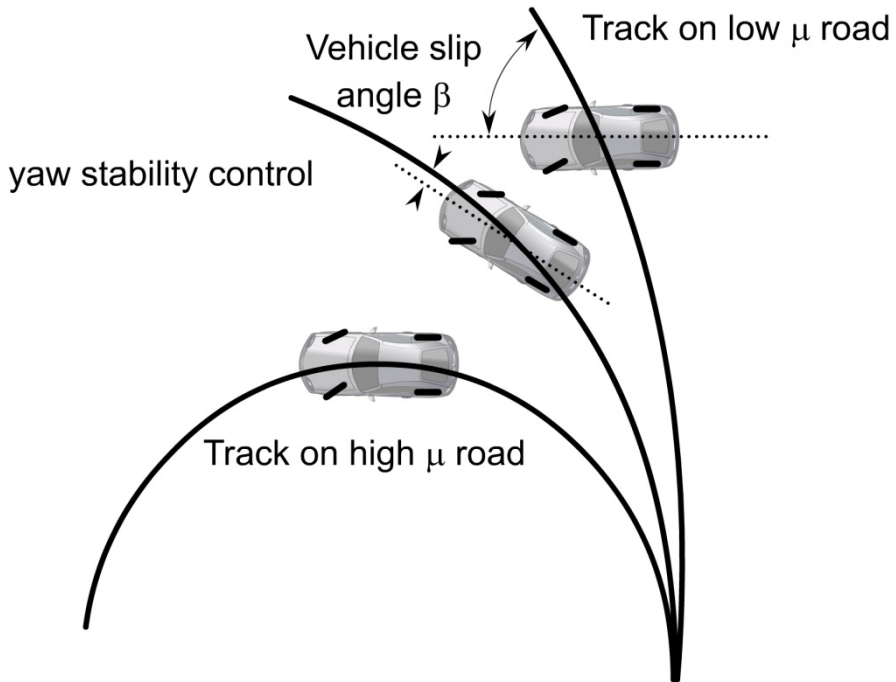


Figure 2-2. The functioning of a yaw control system

Many companies have investigated and developed yaw control systems during the last ten years through simulations and on prototype experimental vehicles. Some of these yaw control systems have also been commercialized on production vehicles. Examples include the BMW DSC3 (Leffler, et. al., 1998) and the Mercedes ESP, which were introduced in 1995, the Cadillac Stabilitrak system (Jost, 1996) introduced in 1996 and the Chevrolet C5 Corvette Active Handling system in 1997 (Hoffman, et.al., 1998).

Three types of stability control systems have been proposed and developed for yaw control:

Differential Braking systems which utilize the ABS brake system on the vehicle to apply differential braking between the right and left wheels to control yaw moment.

Steer-by-Wire systems which modify the driver's steering angle input and add a correction steering angle to the wheels

Active Torque Distribution systems which utilize active differentials and all wheel drive technology to independently control the drive torque distributed to each wheel and thus provide active control of both traction and yaw moment.

By large, the differential braking systems have received the most attention from researchers and have been implemented on several production vehicles. Steer-by-wire systems have received attention from academic researchers (Ackermann, 1994, Ackermann, 1997). Active torque distribution systems have received attention in the recent past and are likely to become available on production cars in the future.

Differential braking systems are the major focus of coverage in this book. They are discussed in section 8.2. Steer-by-wire systems are discussed in section 8.3 and active torque distribution systems are discussed in section 8.4.

2.2 KINEMATIC MODEL OF LATERAL VEHICLE MOTION

Under certain assumptions described below, a kinematic model for the lateral motion of a vehicle can be developed. Such a model provides a mathematical description of the vehicle motion without considering the forces that affect the motion. The equations of motion are based purely on geometric relationships governing the system.

Consider a bicycle model of the vehicle as shown in [Figure 2-3](#) (Wang and Qi, 2001). In the bicycle model, the two left and right front wheels are represented by one single wheel at point A. Similarly the rear wheels are represented by one central rear wheel at point B. The steering angles for the front and rear wheels are represented by δ_f and δ_r respectively. The model is derived assuming both front and rear wheels can be steered. For front-wheel-only steering, the rear steering angle δ_r can be set to zero. The center of gravity (c.g.) of the vehicle is at point C. The distances of points A and B from the c.g. of the vehicle are ℓ_f and ℓ_r respectively. The wheelbase of the vehicle is $L = \ell_f + \ell_r$.

The vehicle is assumed to have planar motion. Three coordinates are required to describe the motion of the vehicle: X , Y and ψ . (X, Y) are inertial coordinates of the location of the c.g. of the vehicle while ψ describes the orientation of the vehicle. The velocity at the c.g. of the vehicle is denoted by V and makes an angle β with the longitudinal axis of the vehicle. The angle β is called the slip angle of the vehicle.