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(continued after index)

Rajesh Rajamani

Vehicle Dynamics and Control

Springer

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For Priya

Mechanical Engineering Series

Frederick F. Ling
Editor-in-Chief

The Mechanical Engineering Series features graduate texts and research monographs to address the need for information in contemporary mechanical engineering, including areas of concentration of applied mechanics, biomechanics, computational mechanics, dynamical systems and control, energetics, mechanics of materials, processing, production systems, thermal science, and tribology.

Series Preface

Mechanical engineering, and engineering discipline born of the needs of the industrial revolution, is once again asked to do its substantial share in the call for industrial renewal. The general call is urgent as we face profound issues of productivity and competitiveness that require engineering solutions, among others. The Mechanical Engineering Series is a series featuring graduate texts and research monographs intended to address the need for information in contemporary areas of mechanical engineering.

The series is conceived as a comprehensive one that covers a broad range of concentrations important to mechanical engineering graduate education and research. We are fortunate to have a distinguished roster of consulting editors, each an expert in one of the areas of concentration. The names of the consulting editors are listed on page vi of this volume. The areas of concentration are applied mechanics, biomechanics, computational mechanics, dynamic systems and control, energetics, mechanics of materials, processing, thermal science, and tribology.

Preface

As a research advisor to graduate students working on automotive projects, I have frequently felt the need for a textbook that summarizes common vehicle control systems and the dynamic models used in the development of these control systems. While a few different textbooks on ground vehicle dynamics are already available in the market, they do not satisfy all the needs of a control systems engineer. A controls engineer needs models that are both simple enough to use for control system design but at the same time rich enough to capture all the essential features of the dynamics. This book attempts to present such models and actual automotive control systems from literature developed using these models.

The control system topics covered in the book include cruise control, adaptive cruise control, anti-lock brake systems, automated lane keeping, automated highway systems, yaw stability control, engine control, passive, active and semi-active suspensions, tire models and tire-road friction estimation. A special effort has been made to explain the several different tire models commonly used in literature and to interpret them physically.

As the worldwide use of automobiles increases rapidly, it has become ever more important to develop vehicles that optimize the use of highway and fuel resources, provide safe and comfortable transportation and at the same time have minimal impact on the environment. To meet these diverse and often conflicting requirements, automobiles are increasingly relying on electromechanical systems that employ sensors, actuators and feedback control. It is hoped that this textbook will serve as a useful resource to researchers who work on the development of such control systems, both in the automotive industry and at universities. The book can also serve as a textbook for a graduate level course on Vehicle Dynamics and Control.

An up-to-date errata for typographic and other errors found in the book after it has been published will be maintained at the following web-site:

http://www.menet.umn.edu/~rajamani/vdc.html

I will be grateful for reports of such errors from readers.

Rajesh Rajamani
Minneapolis, Minnesota
May 2005

Contents

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Several people have played a key role in making this book a reality. I am grateful to Serdar Sezen for highly improving many of my earlier drawings for this book and making them so much more clearer and professional. I would also like to thank Vibhor Bageshwar, Jin-Oh Hahn and Neng Piyabongkarn for reviewing several chapters of this book and offering their comments. I am grateful to Lee Alexander who has worked with me on several research projects in the field of vehicle dynamics and contributed to my learning.

I would like to thank my parents Vanaja and Ramamurty Rajamani for their love and confidence in me. Finally, I would like to thank my wife Priya. But for her persistent encouragement and insistence, I might never have returned from a job in industry to a life in academics and this book would probably have never been written.

Rajesh Rajamani
Minneapolis, Minnesota
May 2005

Chapter 1

INTRODUCTION

The use of automobiles is increasing worldwide. In 1970, 30 million vehicles were produced and 246 million vehicles were registered worldwide. By 2005, 65 million vehicles are expected to be produced and more than 800 million vehicles could be registered (Powers and Nicastri, 2000).

The increasing worldwide use of automobiles has motivated the need to develop vehicles that optimize the use of highway and fuel resources, provide safe and comfortable transportation and at the same time have minimal impact on the environment. It is a great challenge to develop vehicles that can satisfy these diverse and often conflicting requirements. To meet this challenge, automobiles are increasingly relying on electromechanical sub-systems that employ sensors, actuators and feedback control. Advances in solid state electronics, sensors, computer technology and control systems during the last two decades have also played an enabling role in promoting this trend.

This chapter provides an overview of some of the major electromechanical feedback control systems under development in the automotive industry and in research laboratories. The following sections in the chapter describe developments related to each of the following five topics:

a) driver assistance systems
b) active stability control systems
c) ride quality improvement
d) traffic congestion solutions and
e) fuel economy and vehicle emissions

1.1 DRIVER ASSISTANCE SYSTEMS

On average, one person dies every minute somewhere in the world due to a car crash (Powers and Nicastri, 2000). In addition to the emotional toll of car crashes, their actual costs in damages equaled 3% of the world GDP and totaled nearly one trillion dollars in 2000. Data from the National Highway Safety Transportation Safety Association (NHTSA) show that 6.335 million accidents (with 37,081 fatalities) occurred on US highways in 1998 (NHTSA, 1999). Data also indicates that, while a variety of factors contribute to accidents, human error accounts for over 90% of all accidents (United States DOT Report, 1992).

A variety of driver assistance systems are being developed by automotive manufacturers to automate mundane driving operations, reduce driver burden and thus reduce highway accidents. Examples of such driver assistance systems under development include

a) collision avoidance systems which automatically detect slower moving preceding vehicles and provide warning and brake assist to the driver
b) adaptive cruise control (ACC) systems which are enhanced cruise control systems and enable preceding vehicles to be followed automatically at a safe distance
c) lane departure warning systems
d) lane keeping systems which automate steering on straight roads
e) vision enhancement/ night vision systems
f) driver condition monitoring systems which detect and provide warning for driver drowsiness, as well as for obstacles and pedestrians
g) safety event recorders and automatic collision and severity notification systems

These technologies will help reduce driver burden and make drivers less likely to be involved in accidents. This can also help reduce the resultant traffic congestion that accidents tend to cause.

Collision avoidance and adaptive cruise control systems are discussed in great depth in Chapters 5 and 6 of this book. Lane keeping systems are discussed in great detail in Chapter 3.

1.2 ACTIVE STABILITY CONTROL SYSTEMS

Vehicle stability control systems that prevent vehicles from spinning, drifting out and rolling over have been developed and recently commercialized by several automotive manufacturers. Stability control systems that prevent vehicles from skidding and spinning out are often referred to as yaw stability control systems and are the topic of detailed description in Chapter 8 of this book. Stability control systems that prevent roll over are referred to as active roll stability control systems. An integrated stability control system can incorporate both yaw stability and roll over stability control.

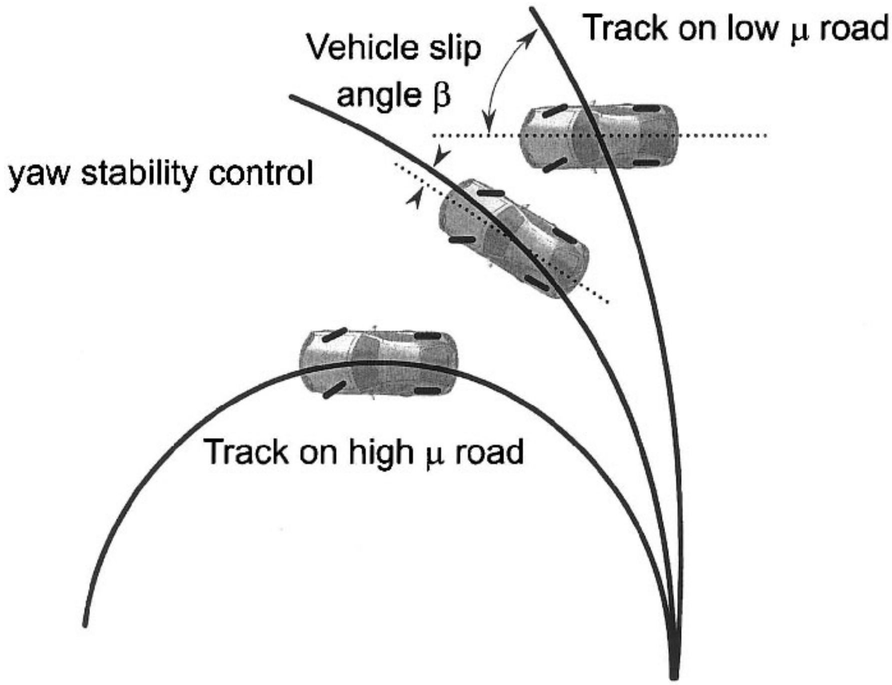

Figure 1-1. The functioning of a yaw stability control system

Figure 1-1 schematically shows the function of a yaw stability 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 1-1. 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 1-1.

Examples of yaw stability control systems that have been commercialized on production vehicles 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).

While most of the commercialized systems are **differential-braking** based systems, there is considerable ongoing research on two other types of yaw stability control systems: **steer-by-wire** and **active torque distribution** control. All three types of yaw stability control systems are discussed in detail in Chapter 8 of this book.

A yaw stability control system contributes to rollover stability just by helping keep the vehicle on its intended path and thus preventing the need for erratic driver steering actions. There is also considerable work being done directly on the development of active rollover prevention systems, especially for sport utility vehicles (SUVs) and trucks. Some systems such as Freightliner's Roll Stability Advisor and Volvo's Roll Stability Control systems utilize sensors on the vehicle to detect if a rollover is imminent and a corrective action is required. If corrective action is required, differential braking is used both to slow the vehicle down and to induce an understeer that contributes to reduction in the roll angle rate of the vehicle. Other types of rollover prevention technologies include Active Stabilizer Bar systems developed by Delphi and BMW (Strassberger and Guldner, 2004). In this case the forces from a stabilizer bar in the suspension are adjusted to help reduce roll while cornering.

1.3 RIDE QUALITY

The notion of using active actuators in the suspension of a vehicle to provide significantly improved ride quality, better handling and improved traction has been pursued in various forms for a long time by research engineers (Hrovat, 1997, Strassberger and Guldner, 2004). Fully active suspension systems have been implemented on Formula One racing cars, for example, the suspension system developed by Lotus Engineering (Wright and Williams, 1984). For the more regular passenger car market, semi-active suspensions are now available on some production vehicles in the market. Delphi's semi-active MagneRide system first debuted in 2002 on the Cadillac Seville STS and is now available as an option on all Corvette models. The MagneRide system utilizes a magnetorheological fluid based shock absorber whose damping and stiffness properties can be varied rapidly in real-time. A semi-active feedback control system varies the shock absorber properties to provide enhanced ride quality and reduce the handling/ ride quality trade-off.

Most semi-active and active suspension systems in the market have been designed to provide improved handling by reducing roll during cornering. Active stabilizer bar systems have been developed, for example, by BMW and Delphi and are designed to reduce roll during cornering without any deterioration in the ride quality experienced during normal travel (Strassberger and Guldner, 2004).

The **RoadMaster** system is a different type of active suspension system designed to specifically balance heavy static loads (www.activesuspension.com). It is available as an after-market option for trucks, vans and SUVs. It consists of two variable rated coil springs that fit onto the rear leaf springs and balance static forces, thus enabling vehicles to carry maximum loads without bottoming through.

The design of passive, active and semi-active suspensions is discussed in great depth in Chapters 6, 7 and 8 of this book.

1.4 TECHNOLOGIES FOR ADDRESSING TRAFFIC CONGESTION

Traffic congestion is growing in urban areas of every size and is expected to double in the next ten years. Over 5 billion hours are spent annually waiting on freeways (Texas Transportation Institute, 1999). Building adequate highways and streets to stop congestion from growing further is prohibitively expensive. A review of 68 urban areas conducted in 1999 by the Texas Transportation Institute concluded that 1800 new lane miles of freeway and 2500 new lane miles of streets would have to be added to keep congestion from growing between 1998 and 1999 ! This level of construction appears unlikely to happen for the foreseeable future. Data shows that the traffic volume capacity added every year by construction lags the annual increase in traffic volume demanded, thus making traffic congestion increasingly worse. The promotion of public transit systems has been difficult and ineffective. Constructing a public transit system of sufficient density so as to provide point to point access for all people remains very difficult in the USA. Personal transportation vehicles will therefore continue to be the transportation mode of choice even when traffic jams seem to compromise the apparent freedom of motion of automobiles.

While the traffic congestion issue is not being directly addressed by automotive manufacturers, there is significant vehicle-related research being conducted in various universities with the objective of alleviating highway congestion. Examples include the development of automated highway systems, the development of "traffic friendly" adaptive cruise control systems and the development of tilt controlled narrow commuter vehicles. These are discussed in the following sub-sections.

1.4.1 Automated highway systems

A significant amount of research has been conducted at California PATH on the development of automated highway systems. In an automated highway system (AHS), vehicles are fully automated and travel together in tightly packed platoons (Hedrick, Tomizuka and Varaiya, 1994, Varaiya, 1993, Rajamani, Tan, et. al., 2000). A traffic capacity that is up to three times the capacity on today's manually driven highways can be obtained. Vehicles have to be specially instrumented before they can travel on an AHS. However, once instrumented, such vehicles can travel both on regular roads as well as on an AHS. A driver with an instrumented vehicle can take a local road from home, reach an automated highway that bypasses congested downtown highway traffic, travel on the automated highway, travel on a subsequent regular highway and reach the final destination, all without leaving his/her vehicle. Thus an AHS provides point to point personal transportation suitable for the low density population in the United States.

The design of vehicle control systems for AHS is an interesting and challenging problem. Longitudinal control of vehicles for travel in platoons on an AHS is discussed in great detail in Chapter 7 of this book. Lateral control of vehicles for automated steering control on an AHS is discussed in Chapter 3.

1.4.2 "Traffic-friendly" adaptive cruise control

As discussed in section 1.1, adaptive cruise control (ACC) systems have been developed by automotive manufacturers and are an extension of the standard cruise control system. ACC systems use radar to automatically detect preceding vehicles traveling in the same lane on the highway. In the case of a slower moving preceding vehicle, an ACC system automatically switches from speed control to spacing control and follows the preceding vehicle at a safe distance using automated throttle control. Figure 1-2 shows a schematic of an adaptive cruise control system.

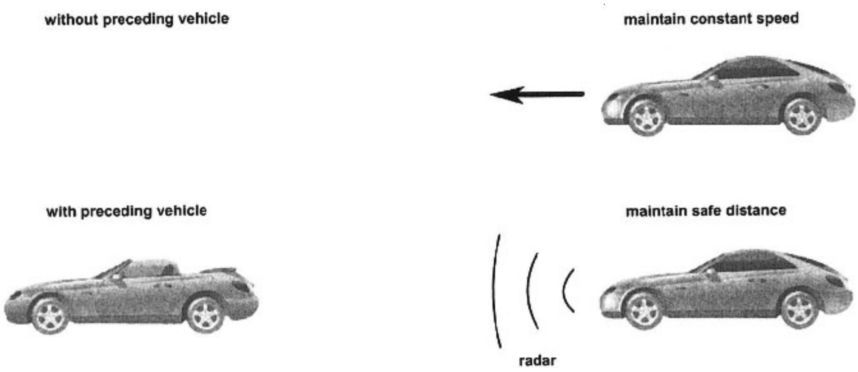

Figure 1-2. Adaptive cruise control

ACC systems are already available on production vehicles and can operate on today's highways. They are being developed by automotive manufacturers as a driver assistance tool that improves driver convenience and also contributes to safety. However, as the penetration of ACC vehicles as a percentage of total vehicles on the road increases, ACC vehicles can also significantly influence the traffic flow on a highway.

The influence of adaptive cruise control systems on highway traffic is being studied by several research groups with the objective of designing ACC systems to promote smoother and higher traffic flow (Liang and Peng, 1999, Swaroop, 1999, Swaroop 1998, Rajamani, 2003). Important issues being addressed in the research include

a) the influence of inter-vehicle spacing policies and control algorithms on traffic flow stability
b) the development of ACC algorithms to maximize traffic flow capacity while ensuring safe operation
c) the advantages of using roadside infrastructure and communication systems to help improve ACC operation.

The design of ACC systems is the focus of detailed discussion in Chapter 6 of this book.

1.4.3 Narrow tilt-controlled commuter vehicles

A different type of research activity being pursued is the development of special types of vehicles to promote better highway traffic. A research