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Rajesh Rajamani

Vehicle Dynamics and Control

Second Edition

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Dr. Rajesh Rajamani
Department of Mechanical Engineering
University of Minnesota
Minneapolis, MN 55455, USA
rajamani@me.umn.edu

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For Priya

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 applications 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-road friction coefficient estimation, rollover prevention, and hybrid electric vehicles. A special effort has been made to explain the several different tire models commonly used in literature and to interpret them physically.

In the second edition, the topics of roll dynamics, rollover prevention and hybrid electric vehicles have been added as Chapters 15 and 16 of the book. Chapter 8 on electronic stability control has been significantly enhanced.

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.

May 2005 and June 2011

Rajesh Rajamani
Minneapolis, Minnesota

Acknowledgments

I am deeply grateful to Professor Karl Hedrick for introducing me to the field of Vehicle Dynamics and Control and for being my mentor when I started working in this field. My initial research with him during my doctoral studies has continued to influence my work. I am also grateful to Professor Max Donath at the University of Minnesota for his immense contribution in helping me establish a strong research program in this field.

I would also like to express my gratitude to my dear friend Professor Darbha Swaroop. The chapters on longitudinal control in this book are strongly influenced by his research results. I have had innumerable discussions with him over the years and have benefited greatly from his generosity and willingness to share his knowledge.

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 Gridsada Phanomchoeng, Vibhor Bageshwar, Jin-Oh Hahn, Neng Piyabongkarn and Yu Wang for reviewing several chapters of this book and offering their comments. I am grateful to Lee Alexander who has worked with me on many 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.

May 2005 and June 2011

Rajesh Rajamani
Minneapolis, Minnesota

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Chapter 1

INTRODUCTION

The use of automobiles is increasing worldwide. In 1970, 30 million vehicles were produced and 246 million vehicles were registered worldwide (Powers and Nicastri, 2000). By 2011, approximately 72 million vehicles are expected to be produced annually and more than 800 million vehicles could be registered.

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 subsystems 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

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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 approximately 6 million accidents (with 35,000 fatalities) occur annually on US highways (NHTSA, 2010). 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 rollover prevention systems and are discussed in depth in Chapter 15 of the book. An integrated stability control system can incorporate both yaw stability and roll over stability control.

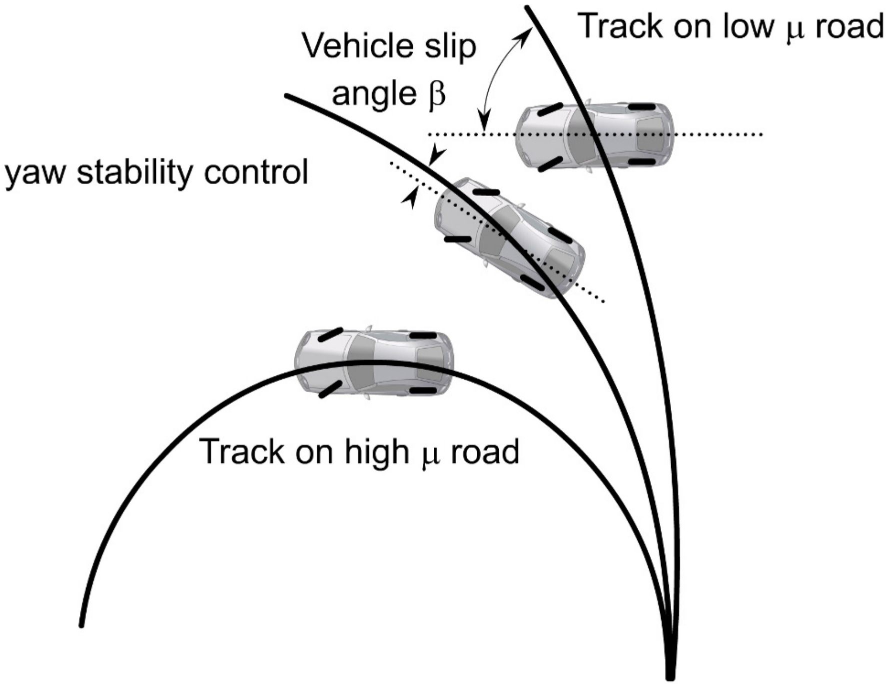

Figure 1-1. The functioning of a yaw stability control system

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