Final Report for Period: 08/2010 - 07/2011

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Principal Investigator: Tsiotras, Panagiotis .

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Organization: Georgia Tech Research Corp

Submitted By:

Tsiotras, Panagiotis - Principal Investigator

Title:

GOALI: Next Generation Active Safety Control Systems for Crash-Avoidance of Passenger Vehicles Using Expert Driver Knowledge

Project Participants

Senior Personnel

Name: Tsiotras, Panagiotis

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Lu, Jianbo

Worked for more than 160 Hours: Yes

Contribution to Project:

Post-doc

Name: Scacchioli, Annalisa

Worked for more than 160 Hours: No

Contribution to Project:

Dr. Annalisa Scacchioli started working on the project in April of 2008. She replaced Dr. Efstathios Velenis who let Georgia Tech for a faculty position in Europe. Dr. Scacchioli was only partially supported by this NSF GOALI. Additional support was provided by Ford Motor Company through a URP and the Army Research Lab.

Graduate Student

Name: Bakolas, Efstathios

Worked for more than 160 Hours: No

Contribution to Project:

Name: Chakraborty, Imon

Worked for more than 160 Hours: Yes

Contribution to Project:

Graduate student enrolled at Georgia Tech in August 2009. He received his MS degree in August 2011.

Name: Kuehme, Daniel

Worked for more than 160 Hours: Yes

Contribution to Project:

Graduate student enrolled at Georgia Tech in January 2010. He received his MS degree in August 2011.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Ford Motor Company

Ford has provided financial support for Dr. E. Velenis and Dr. A. Scacchioli. Ford provided access to their facilities. The point of contact at Ford was the Co-PI, Dr. J. Lu who organized teleconferences and senior personnel visits (for E. Velenis and A. Scacchioli) at the Ford Research Center at Dearborn, Michigan. Ford also made available an instrumented vehicle for a series of tests at the Michigan Proving Grounds (MPG). The vehicle was driven by an expert rally driver (Tim O'Neil) and performed numerous manuevers (trail-braking, pendulum turns). The collected data were used to corroborate the theory developed to generate these maneuvers autonomously via optimal control. The results have been published in the literature. Please see Research Findings section in this report.

Vehicle Control Training, LLC

Vehicle Control Training, LLC (POC: Greg McKinney) is a company that specializes in training military and government security personnel in high-speed driving techniques, especially over rough terrain. We have had extensive discussions with Greg McKinney, Tim O'Neil of the Team O'Neil Rally Driving School and Vehicle Control Center also via our participation in the SAVE (Synthetic Automotive Virtual Environment) program for the development of high-fidelity training driving platforms. Both the PI and one of his former students (E. Velenis) attended the rally school of VCC and were informed about the technical driving techniques used by expert drivers in abnormal driving conditions. In additional, experimental data were collected from a series of test conducted both at the VCC facilities in New Hampshire and the Michigan Proving Grounds of Ford. The latter involved a suitably instrumented Ford SUV vehicle driven by the personnel (Tim O'Neil) of VCC.

Other Collaborators or Contacts

We have collaborated with Vehicle Control Training, LLC (POC: Greg McKinney), a company that specializes in training military and government security personnel in high-speed driving techniques, especially over rough terrain. We have had extensive discussions with Tim O' Neil of the Team O'Neil Rally Driving School and Vehicle Control Center via our participation in the SAVE (Synthetic Automotive Virtual Environment) program for the development of high-fidelity training driving platforms.

We had several discussions with SimCraft (www.simcraft.com) a local Atlanta company that develops small-size, compact and inexpensive full-motion driving simulators. The SimCraft motion platforms were used in the SAVE project; we were in negotiation about having one of these platforms in the PI's lab at Georgia Tech, but these efforts did not materialize, as the SAVE project was canceled by the sponsor.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

A major focus of the automotive industry in terms of active safety is the technological innovation that led to the development of the ABS (Antilock Brake Systems) and ECS (Electronic Stability Control) control systems. Our main research goal within this context is to introduce new algorithms for the control architecture of these automotive systems. Starting from the experience of expert race drivers, we studied and formalized new control algorithms for active safety systems for passenger vehicles.

The ultimate goal is to develop on-demand auto-pilots (i.e., drive management systems - DMS) having elements of expert driving skills. These DMS will use the current and future sensing capabilities of vehicles to detect an impending accident, evaluate the effectiveness of the driver's response, and--when appropriate--intervene to correct the driver's action or inaction.

The first step towards this goal is to identify and classify the most relevant driving techniques used by race drivers. These maneuvers involve skidding, wheel locking, etc. Our goal is to use these maneuvers as elements of a finite state machine ('maneuver automaton') that will be able to automatically schedule the succession of appropriate maneuvers during an emergency.

We have formalized and confirmed the empirical guidelines for executing a Trail-Braking (TB) maneuver, one common cornering technique used in rally-racing. We have shown that a TB maneuver can be generated as a special case of the minimum-time cornering problem subject to specific boundary conditions.

We provided a theoretical interpretation of the 'Left-Foot-Braking,' a technique which is used by expert rally drivers to control the posture of a vehicle over surfaces with low friction coefficient. The basic premise here is that the driver takes advantage of the load transfer between the front and rear axle in order to regulate the friction force at the front and rear tires. This is done by fine-tuning the duration and magnitude of the acceleration/deceleration forces.

We have investigated drifting equilibria (ie, steady-state cornering at high vehicle slip angles) both for single-track and 4-wheel vehicle models, and we have developed feedback control laws to stabilize the vehicle around these equilibria.

Using system inversion and ideas from the theory of flat outputs we have then implemented these ideas to develop control algorithms for the mitigation of post-collision damages during lethal 'T-Bone' collisions at intersections.

Invited Sessions Organized

We have organized invited sessions in the following conferences to promote and disseminate advances in the area of automotive active safety systems

1) Invited session on 'The System of Vehicle, Driver, Environment and Control (VDEC) I and II,' 2009 IEEE International Conference on Systems, Man, and Cybernetics, San Antonio, TX, October 11-14, 2009 (J. Lu and D. Filev session organizers)

2) Two invited sessions on 'Integrated Vehicle Dynamics and Control - I and II,' combined 48th IEEE Conference on Decision and Control and 28th Chinese Control Conference, Shanghai, China, December December 16-18, 2009 (J. Lu, Z. Lin, X.-Y. Lu and P. Tsiotras session organizers)

3) Two invited sessions on 'Integrated Vehicle Dynamics and Control - I and II,' in 49th IEEE Conference on Decision and Control Conference, Atlanta, GA, December 15-17, 2010 (J. Lu, F. Borelli and P. Tsiotras session organizers).

4) Two invited sessions on ''Integrated Vehicle Dynamics and Control - I and II,' in the 50th IEEE Conference on Decision and Control Conference, Orlando, FL, December 12-15, 2011 (J. Lu and P. Tsiotras session organizers).

Special Issue Organized

The two Co-PIs have organized a special issue in the International Journal of Vehicle Autonomous Systems (IJVAS) on 'Autonomous and Semi-Autonomous Control for Safe Driving of Ground Vehicles' (the compete issue can be found at http://www.inderscience.com/browse/index.php?journalID=30&year=2010&vol=8&issue=2/3/4). Nineteen (19) papers were submitted of which 9 were selected to be included in the final special issue.

Publications

Four (4) journal publications and eleven (11) conference publications have resulted from this award

Education Activities

In addition to the education of 2 Post-doctoral students, 2 PhD students and 2 MS students, this research contributed to the education of local high school students via the participation of a local physics teacher to the PI's lab during the summer of 2010.

For more details, please see the attached pdf file.

Findings: (See PDF version submitted by PI at the end of the report)

We have been able to robustly and reliably reproduce the Trail-Braking maneuver using a numerical optimization scheme as described in the paper 'Optimality Properties and Driver Input Parameterization for Trail-Braking Cornering,' by E. Velenis, P. Tsiotras and J. Lu (appeared in the European Journal of Control). The TB maneuver is reproduced as a special case of the minimum-time cornering solution subject to certain endpoint boundary conditions. As opposed to the minimum-time optimization scenarios, we allow free final placement of the vehicle with respect to the width of the road in order to study the optimality of late-apex lines, a common technique used in competition driving. It is shown that indeed, TB is an optimal turning technique, especially if one wants to maximize corner exit velocity and/or one wants to stabilize the vehicle yaw motion as early into the corner as possible.

In order to reduce the optimization search space, we have introduced a convenient parameterization of the control commands as in the paper 'Aggressive Maneuvers on Loose Surfaces: Data Analysis and Input Parameterization,' by E. Velenis, P. Tsiotras, and J. Lu, which was presented in the 15th IEEE Mediterranean Control Conference, June 26-29, 2007, Athens, Greece. Our numerical results indicate that the proposed input parameterization is an appropriate description of the driver's control actions to perform a TB maneuver over a wide range of corner geometries.

We postulated that TB maneuvers consist of three relatively distinct phases. The middle phase is a steady-state cornering with constant velocity, and vehicle slip angle. This motivated us to investigate the relative equilibria (steady-state conditions) during cornering. We have shown that there are indeed such equilibria some of which correspond to nonzero (and often large) vehicle slip angles, thus explaining the large sideslip maneuvers observed in competition driving.

Some of these equilibria are unstable, which means that constant control action is required by the driver to realize these equilibria. We have thus designed LQR and sliding modes controllers to stabilize the vehicle about its cornering equilibria. The results of this work are reported in the paper ``On Steady-State Cornering Equilibria for Wheeled Vehicles with Drift," by Velenis, E., E. Frazzoli, E. and Tsiotras, P., presented to the 48th IEEE Conference on Decision and Control, Shanghai, China, Dec.~16--18, 2009. A journal version of this paper also appeared in the International Journal of Vehicle Autonomous Systems.

Using the previous analyses we were then able to generate aggressive maneuvers to mitigate the so-called 'T-Bone' collisions. These are the most lethal collisions at intersections.

For more details, please see the attached pdf file.

Training and Development:

All personnel involved in this project have become familiar with expert human race driving techniques. Both Dr. Panagiotis Tsiotras and Dr. Efstathios Velenis took a short course on rally driving on loose surfaces and vehicle control under abnormal driving conditions at the facilities of the Team O'Neal Vehicle Training Center at Dalton, New Hampshire. The objective of this work was to encapsulate this knowledge to the next generation of active safety driving systems. Dr. Efstathios Velenis is currently in the faculty of the Mechanical Engineering Department at Brunel University in UK.

Dr. Annalisa Scacchioli started working on the project in March 2008, and she also became familiar with these advanced driving techniques. Dr. Scacchioli also became familiar with the numerical optimization schemes we have developed in our lab to generate optimal vehicle trajectories under abnormal driving conditions. Dr. Scacchioli also brought expertise in nonlinear tracking and hybrid system control. Dr. Scacchioli spend one month in 2009 and one month in 2010 at Ford, collaborating in this project with Ford personnel. Dr. Scacchioli is currently a visiting Assistant Professor at NYU.

The industrial partner representative of this GOALI project (Dr. Jianbo Lu from Ford Motor Co.) became familiar with the advanced technical driving maneuvers used by expert human drivers, and has developed a better understanding of vehicle behavior at the limits of its handling capacity. This knowledge has been used to propose a new control architecture for driver assist, whereby a control system senses impeding unstable behavior of the vehicle and subsequently notifies the driver for the correct (re)action, or -- in extreme cases -- it even intervenes and momentarily takes control of the vehicle to steer it away from the collision.

Several graduate students (E. Bakolas, Imon Chakraborty, Daniel Kuehme) involved in this project have increased their understanding of vehicle dynamics and the application of advanced nonlinear control theory to automotive applications.

Outreach Activities:

In our efforts to involve undergraduates in several aspects of this project, we have contacted the GT Motorsports student club and the GT off-road student racing team at Georgia Tech. The PI met with representatives of the club to educated them about current research activities in the controls community directed towards completely autonomous driving.

As part of the outreach activities the PI participated as a judge in the 9th Annual HBCU-UP National Research Conference, which was held in Atlanta from October 22nd-26th 2008. The HBCU-UP National Research Conference highlights undergraduate student research and institutional strategies to enhance the quality of undergraduate science, technology, engineering, and mathematics (STEM) education and research at HBCUs. The conference is co-sponsored by the National Science Foundation (NSF) HBCU-UP Program and the American Association for the Advancement of Science (AAAS). More than 700 undergraduate African-American students gave oral and poster presentations about their research.

With the help of an RET (Research Experience for Teachers) the PI has participated in the Georgia Intern-Fellowships for Teachers (GIFT) program. GIFT is a program led by the Center for Education Integrating Science, Mathematics, and Computing (CEISMC)(www.ceismc.gatech.edu), a partnership uniting the Georgia Institute of Technology with many other educational groups, schools, corporations, and opinion leaders throughout the state of Georgia, established with the goal to ensure that K-12 students in Georgia receive the best possible preparation in science, mathematics, and technology. GIFT is a collaborative effort designed to enhance mathematics and science experiences of Georgia teachers and their students.

After screening several applications, a physics teacher (Mr. Tengiz Shonia) from a local high school (Campbell HS) was identified and spent 4 weeks in the summer of 2010 at the PI's lab. He later transferred his experience to the classroom, where students became aware of SIMULINK models to represent friction and of control laws to stabilize a vehicle during extreme conditions. One of the PI's graduate students also visited Campbell High and gave a presentation related to this NSF research.

Journal Publications

Velenis, E., and Tsiotras P.,, "Minimum-Time Travel for a Vehicle with Acceleration Limits: Theoretical Analysis and Receding Horizon Implementation", Journal of Optimization Theory and Applications, p. 275, vol. 138, (2008). Published, 10.1007/s10957-008-9381-7

Velenis, E., Tsiotras, P. and J. Lu, "Optimality Properties and Driver Input Parameterization for Trail-Braking Cornering", European Journal of Control, p. 308, vol. 14, (2008). Published, 10.3166/EJC.14.308-320

Velenis, E., Frazzoli, E., and Tsiotras P., "Steady-State Cornering Equilibria and Stabilization for a Vehicle During Extreme Operating Conditions", nternational Journal of Vehicle Autonomous Systems, p. 217, vol. 8, (2010). Published, 10.1504/IJVAS.2010.035797

Velenis, E., Katzourakis, D., Frazolli, E., Tsiotras, P. and Happee, R., "Steady-State Drifting Stabilization of RWD Vehicles", Control Engineering Practice, p. , vol. , (2011). Published, 10.1016/j.conengprac.2011.07.010

Books or Other One-time Publications

Velenis, E., Tsiotras, P., and Lu, J., "Modeling Aggressive Maneuvers on Loose Surfaces: The Cases of Trail-Braking and Pendulum-Turn", (2007). Proceedings, Published
Collection: Proceedings, European Control Conference
Bibliography: Kos, Greece, July 2-5, 2007, pp. 1233-1240

Velenis, E., Tsiotras, P., and Lu, J., "Aggressive Maneuvers on Loose Surfaces: Data Analysis and Input Parameterization", (2007). Proceedings, Published
Collection: Proceedings, 5th IEEE Mediterranean Control
Conference
Bibliography: June 26-29, 2007, Athens, Greece.

Jain, S., Tsiotras, P., and Velenis, E.,, "Optimal Feedback Velocity Profile Generation for a Vehicle with Given Acceleration Limits: A Level Set Implementation", (2008). Proceedings, Published
Collection: Proceedings, 16th Mediterranean Conference on Control and Automation
Bibliography: Ajaccio, Corsica, France, June 25-26, 2008.

Velenis, E., Tsiotras, P. and Lu J.,, "Trail-Braking Driver Input Parameterization for
General Corner Geometry", (2008). Conference Proceedings, Published
Collection: Motorsports Engineering Conference
Bibliography: Concord, NC, Dec.~2--4, 2008.

Velenis, E., Frazzoli, E. and Tsiotras, P., "On Steady-State Cornering Equilibria for Wheeled Vehicles with Drift", (2009). Conference Proceedings, Published

Collection: 48th IEEE Conference on Decision and Control
Bibliography: Shanghai, China, Dec. 16-18, 2009, pp. 3545-3550.

Scacchioli, A., Tsiotras, P., and Lu, J., "Nonlinear-Feedback Vehicle Traction Force Control with Load Transfer for Accident Avoidance", (2009). Conference Proceedings, Published
Collection: ASME Conference
Bibliography: Hollywood, CA, 2009.

J. Lu and D. Filev, "Multi-loop Interactive Control Motivated by Driver in-the-loop Vehicle Dynamics Controls: The Framework", (2009). Conference Proceedings, Published
Collection: IEEE International Conference on Systems, Man, and Cybernetics
Bibliography: October 11-14, 2009, San Antonio,TX.

Bakolas, E. and Tsiotras, P., "On the Generation of Nearly Optimal, Planar Paths of Bounded Curvature and Curvature Gradient", (2009). Conference Proceedings, Published
Collection: American Control Conference
Bibliography: St. Louis, MO, June 10-12, 2009, pp. 385-390.

Dimitar Filev, Jianbo Lu, Kwaku Prakah-Asante, and Fling Tseng, "Real-time Driving Behavior Identification Based on Driver-in-the-loop Vehicle Dynamics and Control", (2009). Proceedings, Published
Collection: 2009 IEEE International Conference on Systems, Man, and Cybernetics
Bibliography: October 11-14, 2009
San Antonio, TX

Jianbo Lu, IEEE Member, Dimitar Filev, IEEE Fellow, Kwaku Prakah-Asante and Fling Tseng, "From Vehicle Stability Control to Intelligent Personal Minder: Real-time Vehicle Handling Limit Warning and Driver Style Characterization", (2009). Proce, Published
Collection: IEEE Symposium Series on Computational Intelligence, Workshop on Computational Intelligence in Vehicles and Vehicular Systems
Bibliography: March 30 - April 2, 2009, Nashville, TN

Velenis, E., Frazzoli, E. and Tsiotras, P., "On Steady-State Cornering Equilibria for Wheeled Vehicles with Drift", (2010). Conference Proceedings, Published
Collection: 48th IEEE Conference on Decision and Control
Bibliography: Shanghai, China, Dec. 16-18, 2009, pp. 3545-3550

Velenis, E., Katzourakis, D., Frazolli, E., Tsiotras, P. and Happee, R., "Stabilization of Steady-State Drifting for a RWD Vehicle", (2010). Conference Proceedings, Published
Collection: 10th International Symposium on Advanced Vehicle Control (AVEC '10)
Bibliography: Loughborough, UK, August 22--26, 2010

Chakraborty, I., Tsiotras, P. and J. Lu, "Mitigation of Unavoidable T-bone Collisions at Intersections Through Aggressive Maneuvering", (2011). Proceedings, Accepted
Collection: 50th IEEE Conference on Decision and Control and European Control Conference
Bibliography: Orlando, FL, Dec. 12-15, 2011

Web/Internet Site

URL(s):

http://www.ae.gatech.edu/labs/dcsl/research-active-safety.html

http://www.ae.gatech.edu/labs/dcsl/research-abnormal.html

Description:

These websites provide updates to the academics and the broader public on the scope of the project, its status, involved personnel, and its implications to technology and society

Other Specific Products

Product Type:

Other inventions

Product Description:

A Vehicle Control System for Mitigating Intersection Crashes, patent disclosure, (inventors: J. Lu, P. Prasad, P. Tsiotras, and E. Velenis)

Sharing Information:

Available to interested parties through Ford Motor Company Technology Licensing Office

Contributions

Contributions within Discipline:

The results from this research have advanced our understanding on the operational regimes of passenger vehicles where nonlinearities play a predominant role. Currently, these regimes are not well understood. Even more, no prior studies had been conducted to take advantage of the dynamics in these regimes for control design. This research was the first to do so and will have an immediate impact on the areas of improved traction/braking control of passenger vehicles and the development of 'intelligent' driving algorithms for accident avoidance.

The approach is based on the observation that only a few individuals have the experience and training to initiate and recover from abnormal driving conditions. These are professional, stunt and race car drivers, who have mastered the driving techniques for performing high-speed evasive maneuvers in diverse environmental conditions. A study of expert driving techniques reveals that professional, race drivers operate the vehicle at the limits of its operational characteristics, often using steering and braking/torquing simultaneously. Novice drivers, instead, apply steering and acceleration/braking commands separately. In this work we initiated, for the first time, a mathematical formalization of the driving control techniques used by expert human drivers. We developed the necessary models to interpret and analyze expert driver maneuvers and we used these models, in conjunction with optimization methods, in order to generate these advanced technical maneuvers in realistic numerical simulations. In particular, trail-braking maneuvers (one of the most common expert driver techniques for cornering) have been faithfully reproduced using this method for a variety of corner geometries.

We analyzed the existence of persistent, steady-state relative equilibria at non-zero vehicle slip vehicle angles. Such relative equilbria (trim trajectories) can be used as building blocks for a variety of aggressive vehicle trajectories. These maneuvers can be used to develop a library of expert driving maneuvers, which when properly combined with a discrete-event supervisor, they can be incorporated in the next generation of active safety systems to mitigate collisions for passenger vehicles.

This work represents the first serious (i.e., mathematical, analytical as opposed to experimental, empirical) investigation of the driving techniques used by expert human drivers. To undertake such a task with a high probability of success, it has been necessary to develop suitable models, which although simple enough to be used for control design, nonetheless capture all the salient features to model vehicles in extreme/abnormal (eg, during skidding) driving conditions. These models, along with the off-line and on-line control algorithms developed in this work provide a new paradigm to control future passenger vehicles during impeding accidents.

The proposed drive management system (DMS) control architecture is based on a novel hybrid architecture that switches between suitable maneuvers inspired by similar expert human driver action. The resulting computer-based DMS compensates for the lack of training and skill of everyday drivers. The research applies advanced techniques from nonlinear control and automata theory to the design of new active safety systems for passenger vehicles.

Contributions to Other Disciplines:

Our work has contributed to the current state-of-the-art in automotive engineering. Specifically, our findings have enhanced our understanding of the behavior of ground vehicles under abnormal driving conditions. Our inspiration has been the aerospace industry. Automotive industry can learn a lot from the practices and experiences of the aerospace industry, where 'fly-by-wire" (FBW) and flight management systems (FMS) have increased the safety, reliability, performance, and fuel efficiency of civil and military aircraft during the last three decades. We believe that similar advances can be made for passenger vehicles. As a matter of fact, controlling a vehicle in the unstable regime of sliding/skidding is not unlike controlling an airplane in deep stall (i.e., sudden loss of lift). Both correspond to nonlinear regions of operation of the vehicle. Albeit difficult to analyze, deep stall is a condition that every pilot should be comfortable with and should know how to recognize and compensate for.

In fact, every licensed pilot (civilian or military, commercial or private) during training is repeatedly engaged in stall conditions by his instructor and he is expected to recover the airplane safely using a series of maneuvers. Nonetheless, we do not require (and probably rightly so) the same level of training from everyday car drivers. Although it is very likely that each driver at some point in his life will have to recover from an abnormal driving condition, he is not trained to do so. How does one resolve this dilemma? The only alternative seems to be a reliable, computer-based drive management system (DMS) that will compensate for the lack of training of everyday drivers.

In addition to the direct application in the automotive industry, our work will also have an impact on:

(i) the development of higher fidelity drive training simulators for the civilian and military sectors. Indeed, such vehicles typically operate in so-called 'abnormal' driving conditions, over rough terrain, often at high speed. Training individuals on the required skills to control the vehicle in these regimes is time-consuming and expensive. Furthermore, maintaining these skills over prolonged periods of time also requires continuous training. Driving simulators in lieu of actual vehicles that reliably represent the said driving conditions can help tremendously in this task.

(ii) control of autonomous and semi-autonomous military vehicles in hazardous terrain. The Army has an understandable vested interest in control algorithms for autonomous navigation in enemy territory. Clearly, the survivability of the vehicle and the mission success rate are a function of the element of surprise and hence the vehicle speed. To date, the state-of-the art limits operation of these vehicles to 20-30 mph. Future autonomous military vehicles have to operate at much higher speeds. At those high-speed regimes the standard assumptions of linear fiction models are completely inadequate. This work has directly contributed to the development of the necessary control algorithms to drive these autonomous vehicles in hazardous terrain.

(iii) the implementation of the recent theory of maneuver automata to a practical problem of enormous interest, thus helping the transitioning from theory to practice.

Finally, the PI was a leading member of the SAVE (Synthetic Automotive Virtual Environment) program for the development of high-fidelity training driving platforms. This program brought together VCC (a company that specializes in training military and security personnel in technical, evasive driving, especially over rough terrain), SimCraft (a local Atlanta company specializing in full motion simulator platforms), the Cold Regions US Army Research Laboratory, and Georgia Tech for the development of a high fidelity drive simulator platform for enabling a larger number of soldiers to be trained in technical, high-speed driving. See also (i) above.

Contributions to Human Resource Development:

Dr. Efstathios Velenis was partially supported by this NSF award from August 2007 till December 2007, upon which time he left Georgia Tech to accept a Lecturer position at Brunel University in UK. There has been involved in supervising many undergraduate and graduate students involved in automotive engineering. He was recently appointed Director of the undergraduate Motorsports program at Brunel.

Dr. Annalisa Scacchioli has been partially supported under this NSF award from March 2008 onwards. The involvement of Dr. Scacchioli with this project has enabled her to increase her knowledge of nonlinear vehicle dynamics and trajectory optimization techniques. She is currently a visiting assistant professor at the mechanical engineering department at NYU.

Mr. Imon Chakraborty is a graduate student, who was fully supported under this NSF project. He joined the School of Aerospace Engineering at Georgia Tech in August 2009 and received his MS degree in August 2011. The title of the his MS thesis project was 'Time-Optimal Control for Collision Mitigation at Intersections'

Mr. Daniel Kuehme is a graduate student, who was fully supported under this NSF project. He joined the School of Aerospace Engineering at Georgia Tech in January 2010 and received his MS degree in August 2011. The title of his MS thesis project was 'Aggressive Maneuvers of Vehicles using Multi-Stage Control.'

This award has also enabled Dr. Jianbo Lu from Ford Motor Company to advance his professional development by his interaction with academia.

This project has enabled the PI (P. Tsiotras) to be involved in new research areas and collaborate with faculty and researchers from other disciplines, as well as from industry.

In addition to the above individuals who were directly involved in this NSF project, two more graduate students participated in research activities relating to the navigation and control of vehicles in high-speed and/or abnormal driving conditions. Specifically, Mr. Efstathios Bakolas worked on the min-time, optimal path- and trajectory generation of ground vehicles subject to acceleration limits. Mr. Raghvendra Cowlagi investigated the problem of path -planning for a vehicle under strict curvature constraints.

Contributions to Resources for Research and Education:

The results of this research will contribute to the development of full-motion driving simulators as a better tool for training drivers. A local Atlanta company (SimCraft, LLC) that specializes in such platforms has been our main partner via our common participation in the SAVE program.

Contributions Beyond Science and Engineering:

Car accidents result in more than 40,000 deaths and 3,000,000 injuries each year in the US alone and many more worldwide. Car accidents are, in fact, the leading cause of mortal injuries globally, accounting for almost 23% of the total. It is the leading cause of death between ages 3-33. By 2020 the World Health Organization predicts that road traffic accidents will be the 3rd leading cause of death due to injury and disease. Besides the social ramifications of these numbers, the cost of traffic accidents to the US economy is estimated to be as high as $300 billion a year. Just the loss of productivity owing to traffic accidents is estimated to cost to the US to be $100 billion a year. Our research will therefore have a large impact on the overall welfare of society, including the technological, healthcare, and insurance sectors.

The results of this research will contribute to the design of the next generation active safety systems for automobiles, leading to a greater reduction of traffic accidents from what is currently possible using ABS and ESP and other similar systems alone. They can also lead to the development of a virtual training environment that can be used to train and reinforce good driving habits to a large number of individuals. By combining these two outcomes, we expect to reduce (and eventually eliminate) vehicle-related accidents both in the military as well as in the civilian sector.

Conference Proceedings

Velenis, E;Tsiotras, P;Lu, J, Aggressive maneuvers on loose surfaces: Data analysis and input parametrization, "JUN 27-29, 2007", 2007 MEDITERRANEAN CONFERENCE ON CONTROL & AUTOMATION, VOLS 1-4, : 1808-1813 2007

Jain, S;Tsiotras, P;Velenis, E, Optimal Feedback Velocity Profile Generation for a Vehicle with Given Acceleration Limits: A Level Set Implementation, "JUN 25-27, 2008", 2008 MEDITERRANEAN CONFERENCE ON CONTROL AUTOMATION, VOLS 1-4, : 1551-1556 2008

Velenis, E;Tsiotras, P, Optimal velocity profile generation for given acceleration limits: Theoretical analysis, "JUN 08-10, 2005", ACC: Proceedings of the 2005 American Control Conference, Vols 1-7, : 1478-1483 2005

Bakolas, E;Tsiotras, P, On the Generation of Nearly Optimal, Planar Paths of Bounded Curvature and Bounded Curvature Gradient, "JUN 10-12, 2009", 2009 AMERICAN CONTROL CONFERENCE, VOLS 1-9, : 385-390 2009

Scacchioli, A;Tsiotras, P;Lu, JB, NONLINEAR-FEEDBACK VEHICLE TRACTION FORCE CONTROL WITH LOAD TRANSFER, "OCT 12-14, 2009", PROCEEDINGS OF THE ASME DYNAMIC SYSTEMS AND CONTROL CONFERENCE 2009, PTS A AND B, : 525-532 2010

Categories for which nothing is reported:

Major Research and Education Activities

Introduction

Driven by federal directives and the public mandate to increase safety, economy and comfort, current passenger cars incorporate a variety of technological advances such as active suspension systems, ABS, differential traction control and electronic stability programs (ESP) to meet these goals. Future vehicles will incorporate even more sophisticated technologies such as four-wheel independent steering, drive-by-wire, brake-by-wire, autonomous navigation and platooning, etc. This research directly supports the development of such active safety systems and facilitates their transfer to production vehicles through a comprehensive collaboration plan with Ford Motor Company as part of the NSF-GOALI Program.

In order to achieve the previous objective we have proposed a control architecture for the next generation of drive management systems (DMS) for passenger vehicles that takes advantage of expert human driver knowledge. The main component of the DMS is the "drive-by-wire" (DBW) control system which–as part of the overall DMS architecture–will *prevent* the driver from taking an incorrect action that would violate the safe limits of the vehicle, and also *help* the driver *recover* from such unsafe regimes. Our proposed approach borrows from well-studied and validated techniques, practices and experiences from the aerospace industry, where "fly-by-wire" (FBW) and flight management systems (FMS) have increased the safety, reliability, performance, and fuel efficiency of civil and military aircraft during the last two decades.

The four cornerstones of our methodology are:

(i) Collaboration with expert race drivers who will provide valuable input on advanced driving techniques to recover from abnormal and dangerous driving conditions;
(ii) Development of mathematical models of these driving techniques;
(iii) On-line implementation of these maneuvers using finite state automata;
(iv) Numerical and experimental validation of the controllers on passenger vehicles at Ford's test facilities.

Research Activities

Maneuver Identification and Classification

A major focus of the automotive industry in terms of active safety is the technological innovation that led to the development of the ABS (Antilock Brake Systems) and ECS (Electronic Stability Control) control systems. Our main research goal within this context is to introduce new algorithms for the control architecture of these automotive systems.

Only a few individuals have the experience and training to initiate and recover from abnormal driving conditions. These are professional, stunt and race car drivers, who have mastered the driving techniques for performing high-speed evasive maneuvers in diverse environmental conditions. A study of expert driving techniques reveals that professional, race drivers operate the vehicle at the limits of its operational characteristics, often using steering and braking/torquing simultaneously. Novice drivers, instead, apply steering and acceleration/braking commands separately. In this work we have initiated for the first time a mathematical formalization of the driving control techniques used by expert human drivers. We have developed the necessary models to interpret and analyze expert driver maneuvers and we have used these models, in conjunction with optimization methods, in order to generate these maneuvers in realistic numerical simulations

We studied the driving techniques of expert race drivers and we formalized new control algorithms for active safety systems for passenger vehicles borrowing from this knowledge.

The ultimate goal is the development of on-demand auto-pilots (i.e., drive management systems - DMS) having elements of expert driving skills. These DMS will use the current and future sensing capabilities of vehicles to detect an impending accident, evaluate the effectiveness of the driver's response, and–when appropriate–intervene to correct the driver's action or inaction.

The first step towards this goal has been the identification and classification of the most relevant driving techniques used by race drivers. These maneuvers involve skidding, wheel locking, etc.

A list and a description of the identified maneuvers are summarized in Table 1.

Table 1: Sample of expert driver techniques.

Technique	**When is it used?**	**Driver's actions**
Left Foot Braking (LFB)	When weight transfer from front to rear axles and vice versa is required	Simultaneous application of throttle and brakes to fine tune the distribution of normal load between front and rear axles.
Trail-Braking	Entering fast on a tight turn; need to yaw fast	Brake hard; progressively release brakes and start steering to initiate sliding; straighten wheels and stop braking once sliding; countersteer and accelerate when aligned to the exit.
Pendulum (Scandinavian Flick)	Connecting tight corners; located near the inner limit of the road with respect to the upcoming turn	Initial slide to the opposite direction of the corner to reduce speed as necessary; turn into the corner accelerating fast and LFB to control understeer.
Handbrake Cornering	Tight turns and not enough space for the pendulum mode	Apply handbrake to reduce rear wheel side traction; initiate drift by turning the steering wheel.
Power Oversteer	Slide for a RWD vehicle	Accelerate hard to reduce rear wheel side traction; initiate drift by turning the steering wheel.

Our goal is to use these maneuvers as elements of a finite state machine ("maneuver automaton") that will be able to automatically schedule the succession of appropriate maneuvers during an emergency.

Trail-Braking Driver Input Parameterization for General Corner Geometry

We have investigated expert driver maneuvering techniques by formalizing and confirming the empirical guidelines for executing a Trail-Braking (TB) maneuver, one common cornering techniques used in rally-racing. We have shown that a TB maneuver can be generated as a special case of the minimum-time cornering problem subject to specific boundary conditions. Since solving the optimization problem for the complete system is numerically too intensive, we have reduced the input search space by using a simple parameterization of the driver's steering, throttle and braking commands. We have shown that the proposed parametrization of the driver's commands can reproduce TB maneuvers for a variety of corner geometries. By allowing free final placement of the vehicle with respect to the width of the road during optimization we have been able to confirm the optimality of late-apex trajectories typically followed by expert rally drivers during the execution of Trail-Braking. We have also investigated the effect of the corner geometry in the baseline TB strategy (steering and acceleration/braking inputs) and we have shown that the basic approach remains valid for a large variety of corner geometry.

The results of this work are summarized in the following papers

– Velenis, E., Tsiotras, P., and Lu, J., "Optimality Properties and Driver Input Parameterization for Trail-Braking Cornering," *European Journal of Control*, Vol. 14, No. 4, pp. 308–320, 2008.
– Velenis, E., Tsiotras, P., and Lu, J. "Modeling Aggressive Maneuvers on Loose Surfaces: The Cases of Trail-Braking and Pendulum-Turn," *European Control Conference*, Kos, Greece, July 2-5, 2007, pp. 1233–1240.
– Velenis, E., Tsiotras, P., and Lu, J. "Aggressive Maneuvers on Loose Surfaces: Data Analysis and Input Parameterization," *15th IEEE Mediterranean Control Conference*, June 26-29, 2007, Athens, Greece.
– Velenis, E., Tsiotras, P. and Lu J., "Trail-Braking Driver Input Parameterization for General Corner Geometry," *Motorsports Engineering Conference*, Concord, NC, Dec. 2–4, 2008.

Mathematical Formalization of the "Left-Foot-Braking" Technique

We provided a theoretical interpretation of the "Left-Foot-Braking," a technique which is used by expert rally drivers to control the posture of a vehicle over surfaces with low friction coefficient by modulating the load transfer between the normal forces on the front and rear axle. The basic premise here is that the driver takes advantage of the load transfer between the front and rear axle in order to regulate the friction force at the front and rear tires. This is done by fine-tuning the duration and magnitude of the acceleration/deceleration forces. In practice, this is achieved by LFB, whereby the driver controls the load transfer effect, hence the forces at the tires. Our goal was to provide a theoretical justification of the use of LFB using optimal control theory.

A simplified two-state hybrid scheme of a "half-car" model with only longitudinal dynamics (but including the transfer load), during the "left-foot braking" manoeuver is shown in Figure 1, where Q_A represents the acceleration dynamics and Q_B is the braking dynamics.

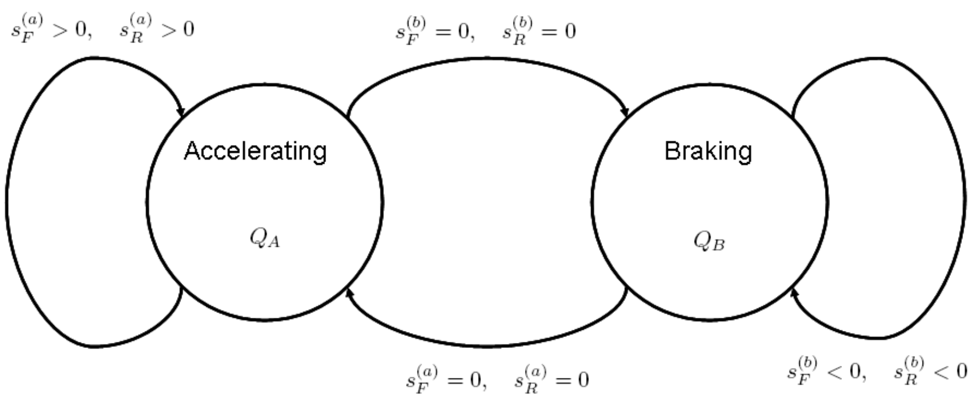


Figure 1: Hybrid system for the "left-foot braking" technique.

The equations of Q_A are given by

$$
\begin{aligned}
\dot{v} &= \mu_F^{(a)}\rho^{(a)} + \mu_R^{(a)}\left(1-\rho^{(a)}\right) \\
r\dot{\omega}_F &= -\frac{m}{I_F} r^2 \mu_F^{(a)}\rho^{(a)} + \frac{r}{I_F}T_F \\
r\dot{\omega}_R &= -\frac{m}{I_R} r^2 \mu_R^{(a)}\left(1-\rho^{(a)}\right) + \frac{r}{I_R}T_R
\end{aligned}
\qquad
\begin{aligned}
\rho^{(a)} &= g\frac{l_R - \mu_R^{(a)}h}{l_R + l_F + (\mu_F^{(a)} - \mu_R^{(a)})h} \\
\mu_F^{(a)} &= D\sin\left(C\arctan(Bs_F^{(a)})\right) \\
\mu_R^{(a)} &= D\sin\left(C\arctan(Bs_R^{(a)})\right) \\
s_F^{(a)} &= \frac{r\omega_F - v}{r\omega_F} \\
s_R^{(a)} &= \frac{r\omega_R - v}{r\omega_R}
\end{aligned}
$$

and similarly for Q_B. In the previous equations, v is the velocity of the vehicle. ω_F and ω_R are the angular velocities of front and rear wheels, I_F and I_R are the polar moments of inertia of the front and rear wheels respectively, T_F and T_R are the torques applied to the front and rear wheels, μ_F and μ_R are the friction coefficients for the front and rear wheels, which depend on the longitudinal slip at the front and rear wheels s_F and s_R, respectively. The constant h denotes the location of the center of mass of the vehicle above the reference line connecting the front and rear axles. It plays a major role in the equations because it models the effect of the load transfer from front to rear wheel during acceleration and deceleration (inertia effect). For $h = 0$ there is no load transfer effect. This case has been extensively treated in the literature. The case when $h \neq 0$ has not been addressed in the literature, but is extremely important for driving over surfaces with low friction coefficient.

The following paper presents the results of this work.

– Scacchioli, A., Tsiotras, P., and Lu, J., "Nonlinear-Feedback Vehicle Traction Force Control with Load Transfer for Accident Avoidance," *ASME Conference*, Hollywood, CA, 2009.

Investigation of Steady-State Cornering Equilibria and Stabilization

We have investigated steady-state cornering conditions for a single-track vehicle model without imposing restrictive conditions on tire slip. Steady-state cornering is defined as cornering along a path of constant curvature, with constant speed and sideslip angle. The steady-state yaw rate is fixed as a function of speed and corner curvature. For each steady-state cornering condition we have calculated the corresponding tire friction forces at the front and rear tires, as well as the required front steering angle and front and rear wheel slip ratios, to maintain constant velocity, turning rate and vehicle sideslip angle. We have analyzed the resulting conditions, identifying stable and unstable relative equilibria. Stable equilibria can be duplicated easily by the driver, whereas unstable equilibria require constant driver response.

Inspired by recent progress in the understanding of advanced driving techniques, we have designed a sliding-mode control scheme stabilizing the unsteady equilibria of the steady-state cornering conditions, using only longitudinal control inputs, i.e, accelerating/braking torques applied at the front and/or rear wheels. The effectiveness of the control scheme is demonstrated by implementing it in a variety of simulation scenarios, including cornering at extreme sideslip angles, similar to the operating regimes met by expert race drivers. The sliding mode architecture is shown in Fig. 2.

We have extended the results to a the case of a 4-wheel, rear-wheel-drive (RWD) vehicle with nonlinear tire characteristics using coupled lateral (steering) and longitudinal (drive torque) control inputs. The effects of the coupling of the rear wheel drive torques is captured through modeling of a differential system. Experimental results performed by a professional driver corroborate very well with high fidelity numerical simulation results obtained via CarSim.

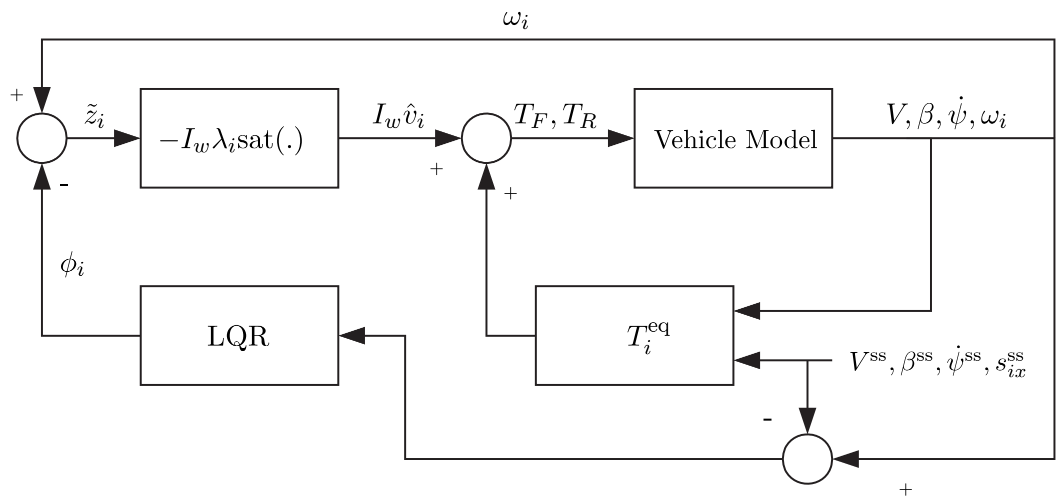


Figure 2: Sliding mode control architecture for the stabilization of steady-state cornering conditions.

Further details of this line of work can be found in the following papers:

- Velenis, E., Frazzoli, E., and Tsiotras P., "Steady-State Cornering Equilibria and Stabilization for a Vehicle During Extreme Operating Conditions," *International Journal of Vehicle Autonomous Systems*, Vol. 8, Nos. 2–4, pp. 217–241, 2010.
- Velenis, E., E. Frazzoli, E. and Tsiotras, P., "On Steady-State Cornering Equilibria for Wheeled Vehicles with Drift," *48th IEEE Conference on Decision and Control*, Shanghai, China, Dec. 16–18, 2009, pp. 3545–3550.
- Velenis, E., Katzourakis, D., Frazolli, E., Tsiotras, P. and Happee, R., "Stabilization of Steady-State Drifting for a RWD Vehicle," *10th International Symposium on Advanced Vehicle Control (AVEC '10)*, Loughborough, UK, August 22–26, 2010.
- Velenis, E., Katzourakis, D., Frazolli, E., Tsiotras, P. and Happee, R., "Steady-State Drifting Stabilization of RWD Vehicles," *Control Engineering Practice*, (accepted July 2011).

Mitigation of Collisions via Aggressive Maneuvering and Vehicle Posture Control

Collisions involving two automobiles can be classified according to the relative orientation of the vehicles at the time of impact. A "T-bone" collision is one where two vehicles collide at approximately right angles, i.e., one vehicle rams the side of the other, which is said to have been "T-boned." Figure 3 shows a typical example of a T-bone collision. T-bone collisions frequently occur when one vehicle runs (i.e., fails to obey) a red light or stop sign and proceeds into a traffic intersection, where it impacts, or is impacted by, another vehicle traveling along a direction perpendicular to it. Such an incursion may be the result of a mechanical failure (stuck throttle, failed brakes), insufficient traction (wet/icy roads), insufficient attention, lack of situational awareness by the driver, etc. Crash statistics from the National Highway Traffic Safety Administration (NHTSA) point to a higher occurrence of traumatic head injuries in T-bone collisions, partly due to the fact that today's vehicles most commonly have better frontal impact protection as compared to side impact protection. Even for an unavoidable collision, there is the possibility of mitigating the effects of the collision by applying intelligent control to (at least) one of the vehicles.

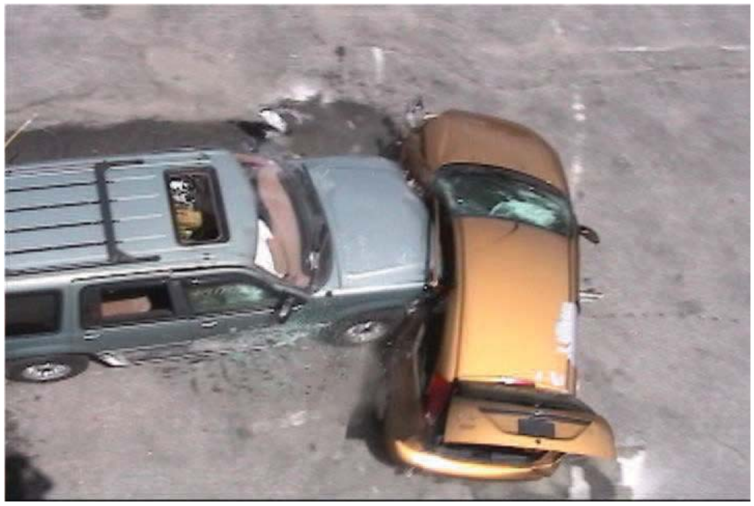
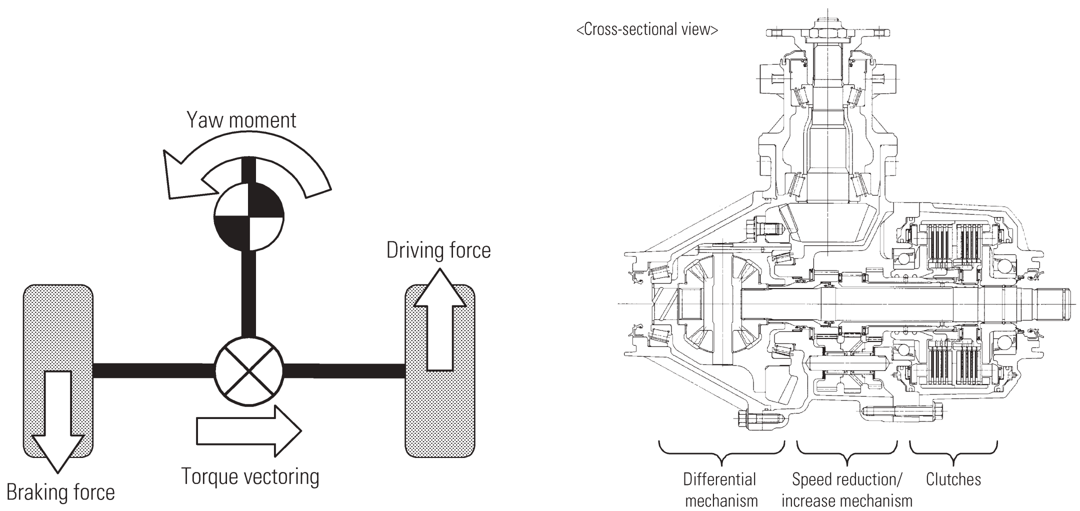


Figure 3: The effects of a T-bone collision can be mitigated by the application of an aggressive maneuver that will change the orientation of the vehicle to a more favorable posture.

In this work, we have analyzed the unavoidable T-bone collision scenario between two vehicles, under the assumption that the intelligent vehicle is mechanically sound, and sufficient road-tire traction exists to allow the execution of the proposed maneuver. The proposed strategy involves a segment of maximum straight-line braking, followed by a rapid yaw rotation that brings the longitudinal axes of the two vehicles into a near parallel alignment. Such a relative pre-impact orientation will allow the residual kinetic energy of the collision to be distributed over a larger surface area, thus mitigating the effects of the collision.



(a) T-bone collision

(b) T-bone collision

Figure 4: The dramatic changes in the yaw vehicle stability required for the T-Bone mitigation maneuver can be implemented with Thrust-Vectoring (TV) technology.

The execution of the proposed maneuver is facilitated by Torque Vectoring (TV) technology, which allows the creation of a “direct” yawing moment, in addition to that generated by front-wheel steering inputs. Torque Vectoring technology seeks to combine the more traditional Differential Braking (DB) and Active Differential (AD) technologies into a single device that can impact a pure yaw rotation on the vehicle. See Fig. 4.

Further details about this work can be found in the following papers:

– Scacchioli, A., Lu, J., Tsiotras, P. and Velenis, E., "Accident Avoidance Using Electronic Posture Control Through Differential Braking," *22nd International Symposium on Dynamics of Vehicles on Roads and Tracks*, (IAVSD'11), Manchester, United Kingdom, Aug. 14–19, 2011.

– Chakraborty, I., Tsiotras, P. and J. Lu, "Mitigation of Unavoidable T-bone Collisions at Intersections Through Aggressive Maneuvering," *50th IEEE Conference on Decision and Control and European Control Conference*, Orlando, FL, Dec. 12–15, 2011 (accepted).

A Framework for Multi-loop Interactive Control for Driver-in-the-Loop

Today's vehicles are equipped with many electronic devices. Those devices improve vehicle performance, comfort and safety. While human-centered vehicle design is increasing the utility of electronic devices, the interaction between driver and electronic devices remains critical for the further advance of vehicular systems. Correct decision and action on behalf of the driver can increase the effectiveness of the electronic devices and minimize traffic accidents. On the other hand, because of the possibility of driver error (such as misjudgment, inattention, distraction, or incorrect response to an emergency, etc.), which are the cause of 45% to 75% of roadway collisions, electronic devices need to be more intelligent; we need to develop systems that can differentiate different scenarios and intervene accordingly. They need to serve as cooperative agents to work with the driver, e.g., to adapt to the driver's behavior; to understand the driving situation, the driver intent, and the driver's controllability; to detect driver's error; to provide proper driver support. Such agents can ultimately lead to fully autonomous vehicles where the driver's role is replaced by intelligent electronic devices.

Before such intelligent and cooperative agents become a reality in mass produced vehicles, the fundamentals around the driver-in-the-loop vehicle controls need further attention. As part of this vision on the interaction between driver control and electronic system controls, we have investigated how to use the interaction for scenario identification and control design, and how to support the driver upon the detection of an emergency. These topics are generalized to a generic framework that likely fits many other control systems including a human operator. Specifically, the system of interest has multiple control loops and each loop has its own sensing, decision making and actuation. One of the loops is the primary loop (e.g. the driver control loop) which determines the system goal with a continuous activation. All the other loops support the primary loop, namely, assist the primary loop to achieve a control performance goal. Although the output of the controller in the primary loop (primary controller) can be observed by the controllers in the secondary loops (secondary controllers), the control structure and parameters of the primary controller are unknown. Such uncertainties in the primary controller corresponds to the unpredictable behavior of a human driver, which might be affected by a number of factors that are not observed by the secondary controllers, e.g. driver's physical, cognitive, or psychological states. The control problem is to design the secondary controllers to help achieve the overall control goal of the system. The control schemes considered here are rather non-traditional, including *passive control*, *semi-autonomous control*, and *autonomous control*. Those control schemes are discretely active or on-demand in nature. Abusing the terminology used by hybrid system, we use *hybrid control* to infer the above non-traditional controls. Figure 5 shows the flow chart of the proposed Interactive Multi-Loop Control System (IMCS).

Further details on the approach are given in the papers:

– Lu, J. and Filev, D., "Multi-loop Interactive Control Motivated by Driver-in-the-loop Vehicle Dynamics Controls: The Framework" *48th IEEE Conference on Decision and Control*, Shanghai, China, Dec. 16-18, 2009, pp. 3569–3574.

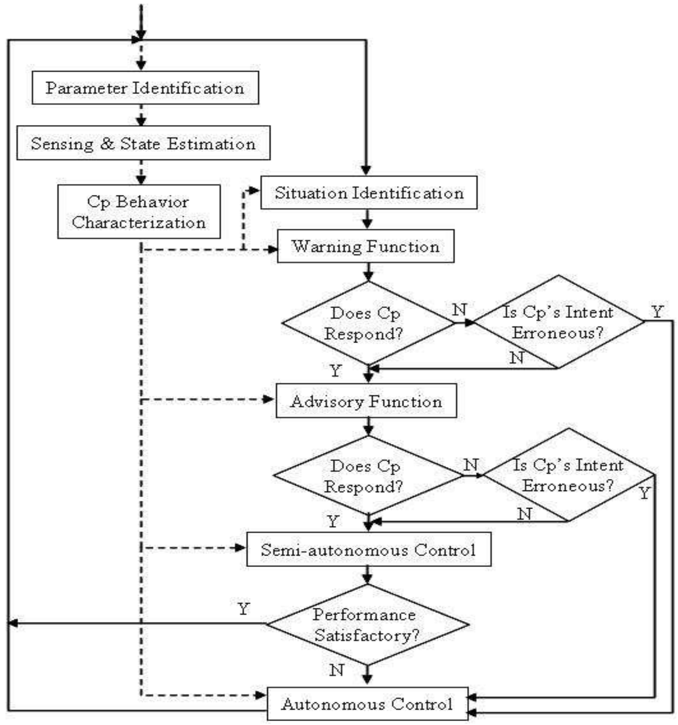


Figure 5: The flow chart for the control of an IMCS.

- Filev, D., Lu, J., Prakah-Asante, K. and Tseng, F., "Real-time Driving Behavior Identification Based on Driver-in-the-loop Vehicle Dynamics and Control," *2009 IEEE International Conference on Systems, Man, and Cybernetics*, October 11-14, 2009 San Antonio, TX.
- Lu, J., Filev, D., Prakah-Asante, K. and Tseng, F., "From Vehicle Stability Control to Intelligent Personal Minder: Real-time Vehicle Handling Limit Warning and Driver Style Characterization," *2009 IEEE Symposium Series on Computational Intelligence*, March 30-April 2, 2009, Nashville, TN.

Educational Activities

Dr. Efstathios Velenis completed his post-doctoral studies, and left Georgia Tech in December of 2007. He joined Brunel University in UK as a Lecturer in the Department of Mechanical Engineering. His main research interests will continue to be in the area of automotive system control.

Dr. Annalisa Scacchioli worked–partially–under this project from March 2008. Dr. Scaccioli's prior experience was in nonlinear regulation, hybrid systems and automotive (powertrain) control. Dr. Scacchioli received her Ph.D. degree from the University of Rome. She has also held research appointments with Ohio State and the University of California at Berkeley. Dr. Scacchioli spent two weeks in September of 2008 at Ford Motor Company in Dearborn, Michigan working with Dr. Lu on this project.

In January 2008 another graduate student, Oncu Ararat, joined the project. Mr. Ararat is a graduate from Istanbul Technical University in Turkey. He was selected among several other individuals who applied to join the graduate program at Georgia Tech's School of Aerospace Engineering after an announcement posted by the PI at the e-letter control discussion list on the internet. Mr. Ararat's prior expertise was on dynamics and control of automotive systems; he was a member of the Automotive Systems Laboratory at ITU headed by Prof. Levent. The latter gave his highest recommendations for hiring Mr. Ararat. Unfortunately, Mr. Ararat had to return to his home country in February 2008, due to some unexpected family reasons. This has been an unplanned and unfortunate event.

In August 2009 a new graduate student, Imon Chakraborty, joined the School of Aerospace Engineering and started work on this project as part of his MS thesis. Mr. Chakraborty's undergraduate degree is in Mechanical Engineering from NIT Tiruchirappalli in India. He graduated on top of his class and he was highly recommended by his former advisors. He received his MS degree in August 2011. The title of his MS thesis project was "Time-Optimal Control for Collision Mitigation at Intersections."

Another new MS student (Daniel Kuehme) joined this research project in January 2010. Daniel graduated from Georgia Tech AE with honors (GPA 3.95/4.00). He received his MS degree in August 2011 and he is continuing his doctoral studies at Georgia Tech. The title of his MS thesis project was "Aggressive Maneuvers of Vehicles using Multi-Stage Control."

Two other students contributed to the results of this project, although they were not funded directly by this project. Specifically, Raghvendra Cowlagi worked on path planning of wheeled vehicles under kinodynamic motion constraints. He received his PhD in May 2011. The title of his PhD dissertation was "Hierarchical Motion Planning for Autonomous Aerial and Terrestrial Vehicles." Dr. Cowlagi is currently a post-doctoral student at MIT. Finally, Efstathios Bakolas also contributed–partially–to this project, in particular on path-planning of wheeled vehicles under turn radius curvature constraints. He is expected to graduate with his PhD degree in December of 2011.

<u>Outreach Activities</u>

In our efforts to involve undergraduates in several aspects of this project, we have contacted the GT Motorsports student club and the GT off-road student racing team at Georgia Tech. During a meeting with the PI, members of the GT off-road team were informed about the activities supported by this project.

As part of the outreach activities the PI participated as a judge in the 9th Annual HBCU-UP National Research Conference, which was held in Atlanta from October 22nd-26th 2008. The HBCU-UP National Research Conference highlights undergraduate student research and institutional strategies to enhance the quality of undergraduate science, technology, engineering, and mathematics (STEM) education and research at HBCUs. The conference is co-sponsored by the National Science Foundation (NSF) HBCU-UP Program and the American Association for the Advancement of Science (AAAS). More than 700 undergraduate African-American students gave oral and poster presentations about their research.

As part of the Georgia Tech's Intern-Fellowship for Teachers (GIFT) program (`www.ceismc.gatech.edu/gift`) and with additional support from the NSF RET (Research Experience for Teachers) supplement award, we invited a local high school physics teacher (Mr. Tengiz Shonia at Campbell High School) to spend 4 weeks in the PI's lab during the summer of 2010. GIFT is a program led by the Center for Education Integrating Science, Mathematics, and Computing (CEISMC), a partnership uniting the Georgia Institute of Technology with many other educational groups, schools, corporations, and opinion leaders throughout the state of Georgia, towards enhancing mathematics and science experiences of Georgia teachers and their students. In these fellowships, teachers are involved in cutting edge scientific research, data analysis, curriculum development and real-world inquiry and problem solving. GIFT follows up with the teacher during the school year to provide support and oversee the transfer of the summer experience into the classroom. Indeed, Mr. Shonia introduced in his advanced physics placement class elements of friction modeling and simple control law development of passenger vehicle stability using SIMULINK. One of the PI's graduate students (Dan Kuehme) also visited Campbell HS and gave a presentation of his research on vehicle control during extreme conditions.

Activities to Educate Professionals and Disseminate the Results

Invited Conference Sessions Organized

The PI and the Co-PI from Ford organized invited sessions in the following conferences to promote and disseminate advances in the area of automotive active safety systems.

– Invited session on "The System of Vehicle, Driver, Environment and Control (VDEC) I and II," *2009 IEEE International Conference on Systems, Man, and Cybernetics*, San Antonio, TX, October 11-14, 2009 (J. Lu and D. Filev session organizers).
– Invited session on "Integrated Vehicle Dynamics and Control - I and II," combined *48th IEEE Conference on Decision and Control and 28th Chinese Control Conference*, Shanghai, China, December 16-18, 2009 (J. Lu, Z. Lin, X.-Y. Lu and P. Tsiotras session organizers).
– Invited session on "Integrated Vehicle Dynamics and Control - I and II," combined *49th IEEE Conference on Decision and Control*, Atlanta, GA, December 15-17, 2010 (J. Lu, F. Borelli and P. Tsiotras session organizers).
– Invited session on "Integrated Vehicle Dynamics and Control - I and II," combined *50th IEEE Conference on Decision and Control*, Orlando, FL, December 12-15, 2011 (J. Lu and P. Tsiotras session organizers).

Special Journal Issue Organized

The two Co-PIs of this GOALI NSF project have organized a special issue in the *International Journal of Vehicle Autonomous Systems (IJVAS)* on "Autonomous and Semi-Autonomous Control for Safe Driving of Ground Vehicles" (`http://www.inderscience.com/browse/index.php?journalID=30&year=2010&vol=8&issue=2/3/4`). Nineteen (19) papers have been submitted and are currently under review, nine (9) of which have been accepted for publication.

Publications

The following publications resulted from the direct or indirect support of this research award.

1. Velenis, E., and Tsiotras P., "Minimum-Time Travel for a Vehicle with Acceleration Limits: Theoretical Analysis and Receding Horizon Implementation," *Journal of Optimization Theory and Applications*, Vol. 138, No. 2, pp. 275–296, 2008, doi:10.1007/s10957-008-9381-7.

2. Velenis, E., Tsiotras, P., and Lu, J., "Optimality Properties and Driver Input Parameterization for Trail-Braking Cornering," *European Journal of Control*, Vol. 14, No. 4, pp. 308–320, 2008, doi:10.3166/EJC.14.308-320.

3. Velenis, E., Frazzoli, E., and Tsiotras P., "Steady-State Cornering Equilibria and Stabilization for a Vehicle During Extreme Operating Conditions," *International Journal of Vehicle Autonomous Systems*, Vol. 8, Nos. 2–4, pp. 217–241, 2010, doi:10.1504/IJVAS.2010.035797

4. Velenis, E., Katzourakis, D., Frazolli, E., Tsiotras, P. and Happee, R., "Steady-State Drifting Stabilization of RWD Vehicles," *Control Engineering Practice*, doi:10.1016/j.conengprac.2011.07.010. (accepted July 2011).

5. Velenis, E., Tsiotras, P., and Lu, J. "Modeling Aggressive Maneuvers on Loose Surfaces: The Cases of Trail-Braking and Pendulum-Turn," *European Control Conference*, Kos, Greece, July 2-5, 2007, pp. 1233–1240.

6. Jain, S., Tsiotras, P., and Velenis, E., "Optimal Feedback Velocity Profile Generation for a Vehicle with Given Acceleration Limits: A Level Set Implementation," *16th IEEE Mediterranean Conference on Control and Automation*, Ajaccio, Corsica, France, June 25-26, 2008, pp. 451–456.

7. Velenis, E., Tsiotras, P. and Lu J., "Trail-Braking Driver Input Parameterization for General Corner Geometry," *Motorsports Engineering Conference*, Concord, NC, Dec. 2–4, 2008, SAE Paper 2008-01-2986.

8. Bakolas, E. and Tsiotras, P., "On the Generation of Nearly Optimal, Planar Paths of Bounded Curvature and Curvature Gradient," *American Control Conference*, St. Louis, MO, June 10–12, 2009, pp. 385-390.

9. Scacchioli, A., Tsiotras, P., and Lu, J., "Nonlinear-Feedback Vehicle Traction Force Control with Load Transfer for Accident Avoidance," *ASME Dynamic Systems and Control Conference (DSCC'09)*, Hollywood, CA, Oct. 12–14, 2009, pp. 525-532.

10. Lu, J. and Filev, D., "Multi-loop Interactive Control Motivated by Driver-in-the-loop Vehicle Dynamics Controls: The Framework" *48th IEEE Conference on Decision and Control*, Shanghai, China, Dec. 16-18, 2009, pp. 3569–3574.

11. Filev, D., Lu, J., Prakah-Asante, K. and Tseng, F., "Real-time Driving Behavior Identification Based on Driver-in-the-loop Vehicle Dynamics and Control," *2009 IEEE International Conference on Systems, Man, and Cybernetics*, October 11-14, 2009 San Antonio, TX.

12. Lu, J., Filev, D., Prakah-Asante, K. and Tseng, F., "From Vehicle Stability Control to Intelligent Personal Minder: Real-time Vehicle Handling Limit Warning and Driver Style Characterization," *2009 IEEE Symposium Series on Computational Intelligence*, March 30-April 2, 2009, Nashville, TN.

13. Velenis, E., Frazzoli, E. and Tsiotras, P., "On Steady-State Cornering Equilibria for Wheeled Vehicles with Drift," *48th IEEE Conference on Decision and Control*, Shanghai, China, Dec. 16–18, 2009, pp. 3545–3550.

14. Velenis, E., Katzourakis, D., Frazolli, E., Tsiotras, P. and Happee, R., "Stabilization of Steady-State Drifting for a RWD Vehicle," *10th International Symposium on Advanced Vehicle Control (AVEC)*, Loughborough, UK, August 22–26, 2010.

15. Chakraborty, I., Tsiotras, P. and J. Lu, "Mitigation of Unavoidable T-bone Collisions at Intersections Through Aggressive Maneuvering," *50th IEEE Conference on Decision and Control and European Control Conference*, Orlando, FL, Dec. 12–15, 2011 (to appear).

Findings

Input Parameterization for General Corner Geometry

In the following, we reproduce the Trail-Braking maneuver using a numerical optimization scheme as in the paper "Optimality Properties and Driver Input Parameterization for Trail-Braking Cornering," by E. Velenis, P. Tsiotras and J. Lu (to appear in the *European Journal of Control*). The TB maneuver is reproduced as a special case of the minimum-time cornering solution subject to certain endpoint boundary conditions. As opposed to the optimization scenarios in the previous reference, we allow free final placement of the vehicle with respect to the width of the road in order to study the optimality of late-apex lines. We consider a single-track vehicle model with nonlinear tire friction characteristics and a static map to calculate the longitudinal load transfer during acceleration/braking.

The baseline solution corresponds to the minimum-time cornering problem for a 90deg corner on a low μ surface ($\mu = 0.5$), and is shown in Fig. 6.

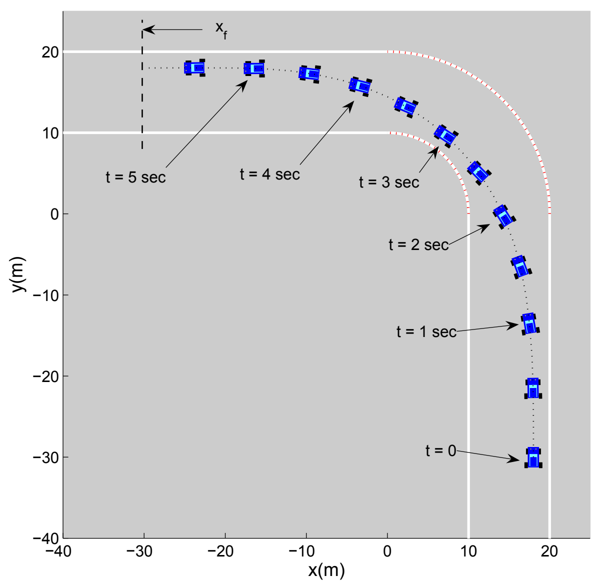


Figure 6: Baseline minimum-time cornering: vehicle trajectory.

In order to validate the robustness of the approach with respect to several corner geometries, we reproduced several TB maneuvers via numerical optimization using a high fidelity vehicle model for a variety of corner geometries. Specifically, we have used CarSim to integrate the full-car vehicle dynamics of an All-Wheel-Drive sedan. The vehicle model incorporates realistic engine, transmission and braking system characteristics. Besides the steering command, the control inputs to be optimized are independent throttle and brake commands. In order to reduce the optimization search space, we have introduced a convenient parameterization of the control commands as in the paper "Aggressive Maneuvers on Loose Surfaces: Data Analysis and Input Parameterization," by E. Velenis, P. Tsiotras, and J. Lu, which was presented in the *15th IEEE Mediterranean Control Conference*, June 26-29, 2007, Athens, Greece. The steering, braking and throttle command parameterizations for the Trail-Braking maneuver used in that reference are shown in Figures 7(a), (b) and (c). Figure 8 shows the corresponding optimal vehicle speed, vehicle slip angle, and front and rear axle normal loads.

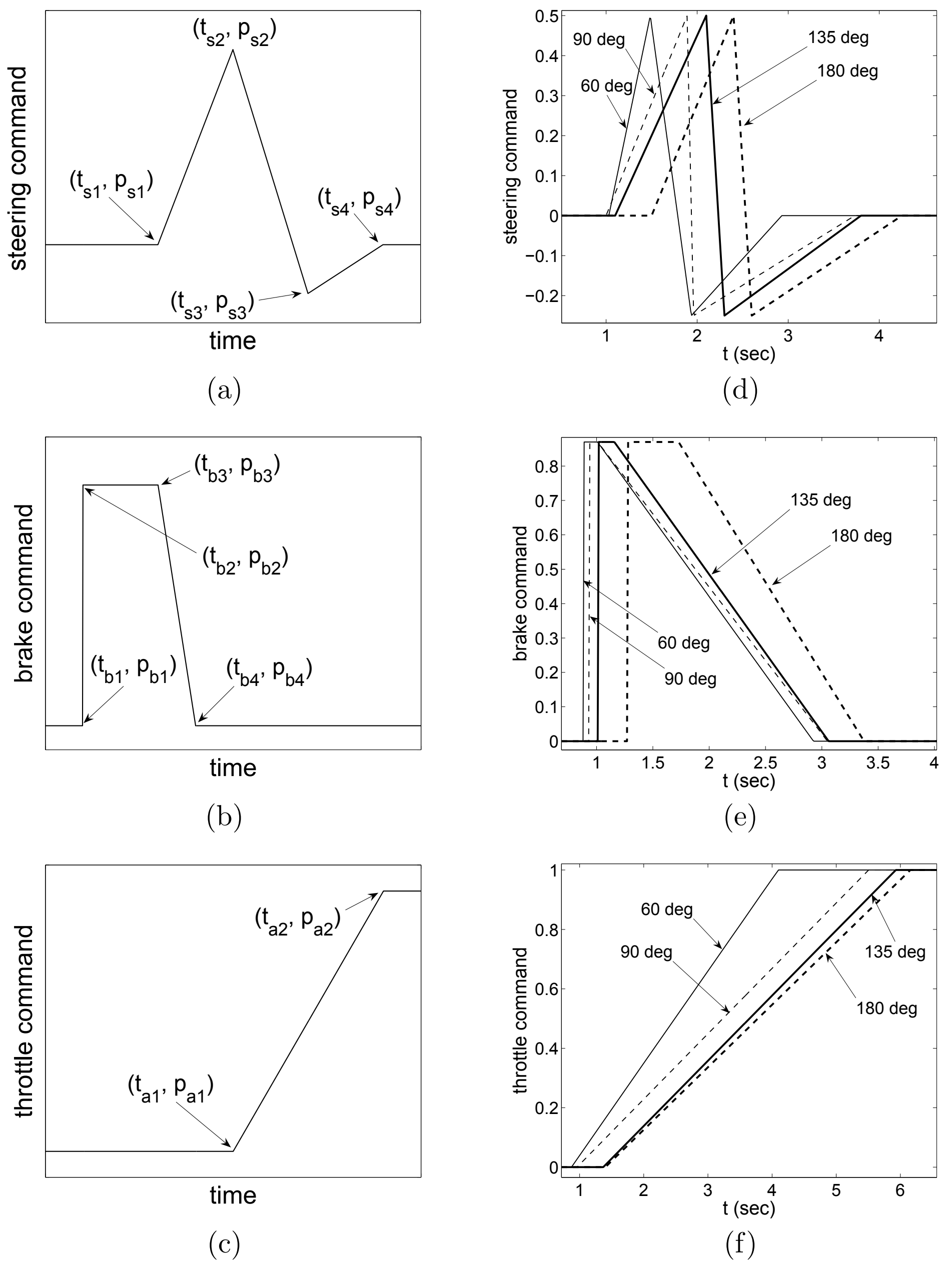


Figure 7: Parameterized steering (a), braking (b) and throttle (c) inputs for Trail-Braking; optimal steering (c), brake (d) and throttle (e) inputs through the 60, 90, 135 and 180deg corners.

Figures 9 and 10 show the optimal trajectories of the vehicle along the 60, 135 and 180 deg corners respectively. The simulation continues up to 45 m distance after the center of the corner (that is, 30 m after the end of the optimization) with maximum acceleration, in order to demonstrate that the boundary conditions at the end of the corner have been satisfied. Figure 10 also demonstrates one of the resulting optimal trajectories using the 3D visualization tool of CarSim. We conclude that the proposed input parameterization of Fig. 7 is an appropriate description of the driver's control actions to perform a TB maneuver over a wide range of corner geometries.

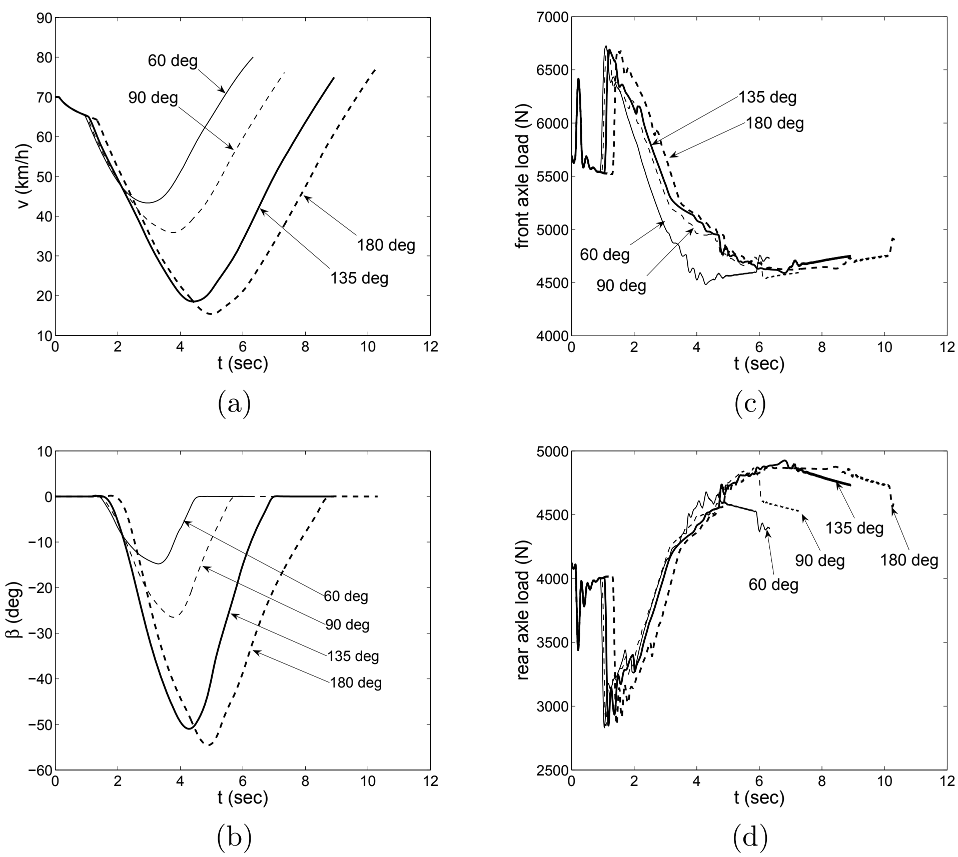
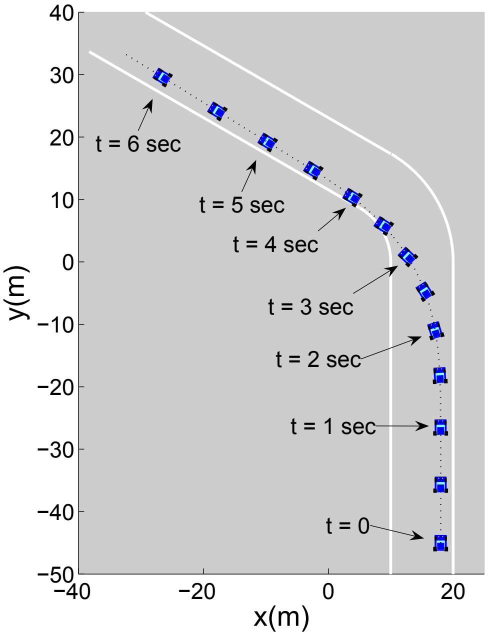
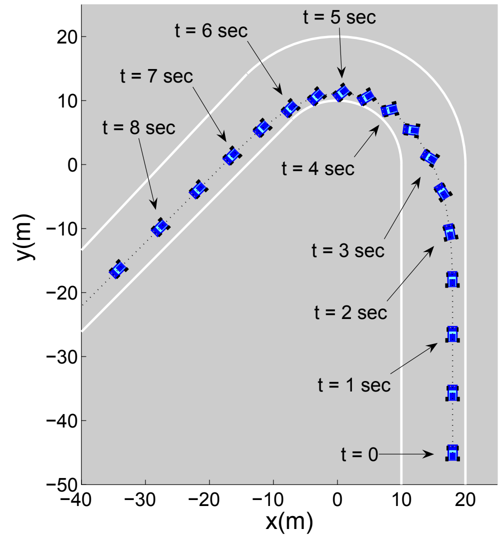


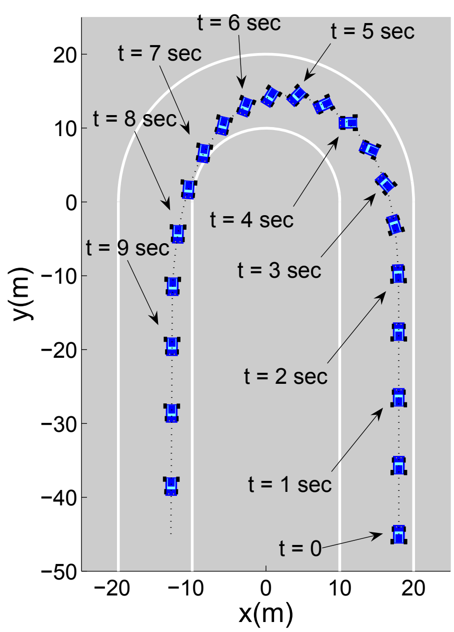
Figure 8: Optimal vehicle speed (a), vehicle slip angle (b), front and rear axle normal loads (c)-(d) through the 60, 90, 135 and 180 deg corners.



(a) 60 deg



(b) 135 deg



(c) 180 deg

Figure 9: Trail-Braking through a 60 deg, 135 deg and 180 deg corner.

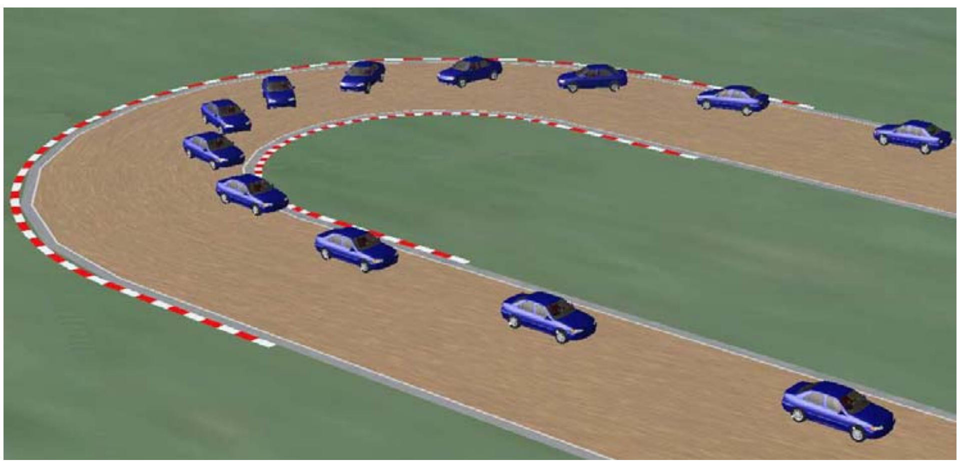
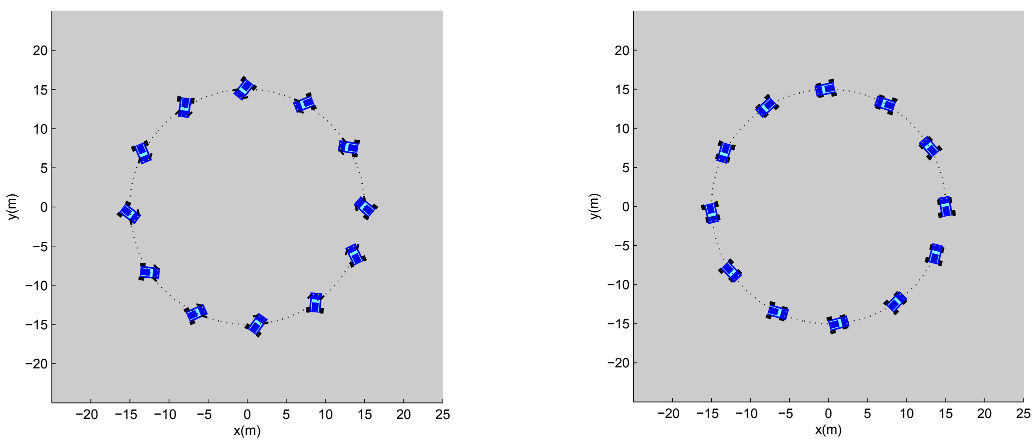


Figure 10: Three-dimensional visualization of Trail-Braking through a 180 deg corner.

Steady-State Equilibria and Stabilization During Cornering

Given constant values for V^{ss}, R^{ss} and β^{ss} we can compute the corresponding rear and front longitudinal and lateral tire friction forces. Pacejka's Magic formula can then be used to solve for the required steady-state slip coefficients s_R^{ss}, s_{Rx}^{ss} and s_{Ry}^{ss}. We can determine the stability characteristics of the derived steady-state cornering conditions by linearizing the equations of motion about a steady-state cornering equilibrium. It turns out that several of these equilibria are unstable. For the unstable equilibria we have designed an LQR stabilizing controller assuming front and rear wheel longitudinal slips (slip ratios) s_{Fx} and s_{Rx} as the control inputs. We assume that the steering angle δ as a parameter fixed to its steady-state value as calculated above, and we demonstrate stabilization of the system using purely longitudinal control. This is in accordance to vehicle handling and control by expert rally drivers, who regulate throttle and brake inputs to stabilize a vehicle during cornering using longitudinal control only, by taking advantage of the longitudinal load transfer during acceleration and deceleration.

Figures 11(a) and 11(b) show two typical cases of steady-state cornering resulting from our analysis.



(a) $\beta = 50\,\mathrm{deg}$ (b) $\beta = 10\,\mathrm{deg}$

Figure 11: Typical cases of steady-state cornering results.

These results have been validated against a high fidelity vehicle model, which take into account all four wheels, as well as the suspension dynamics. Figures 12 show the results when the vehicle suspension dynamics are included in the model.

The resulting vehicle trajectories with the LQR stabilization controller are shown in Fig. 13 with the corresponding states $(V, \beta, \dot{\psi})$ and control inputs s_{ix} shown in Fig. 14. In these simulation scenarios the steering angle δ is fixed at its steady-state value.

The previous results were derived under the assumption that we can control directly the wheel slips. In reality, our control inputs are the wheel torques and front wheel steering angle, instead. We have therefore designed a sliding-mode control scheme to stabilize the vehicle with respect to steady-state equilibria incorporating the wheel angular rate dynamics, and using independent front and rear wheel torque control. The results are shown in Fig. 15.

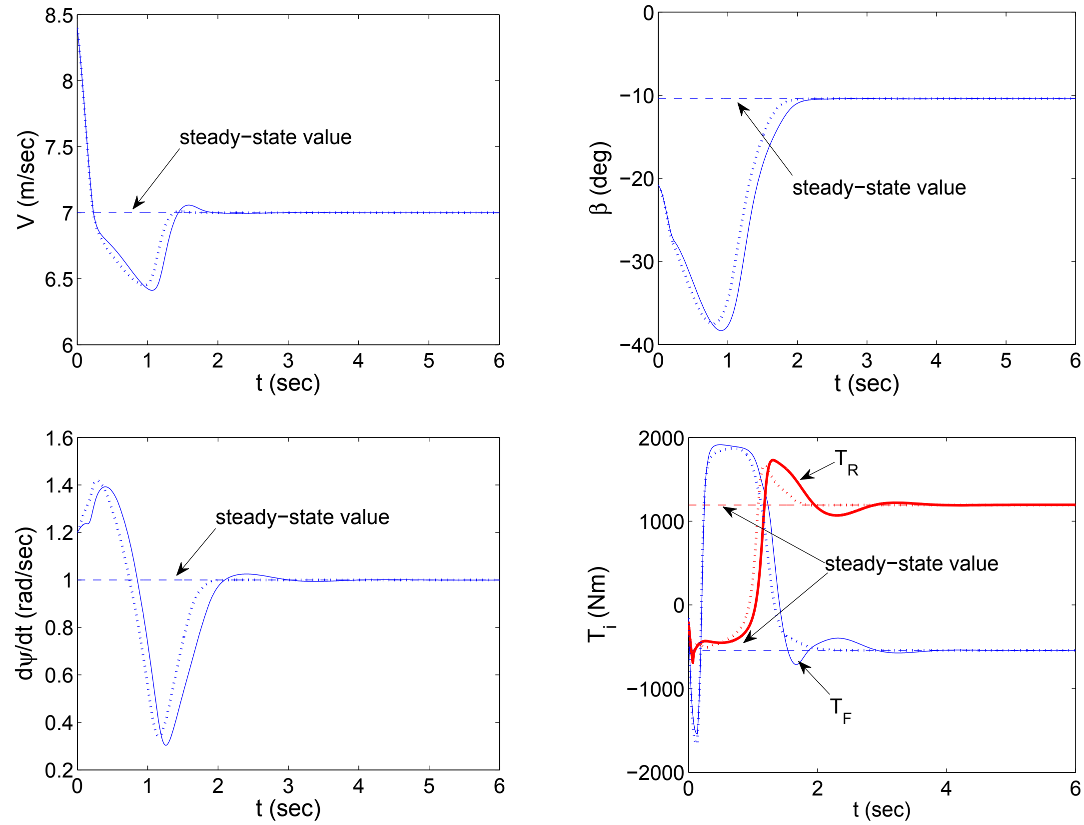
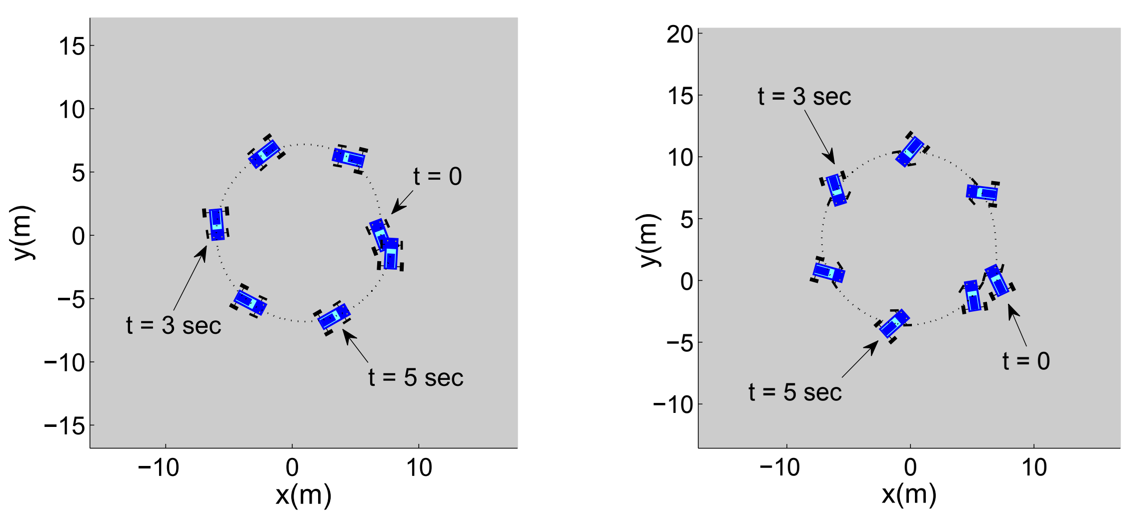


Figure 12: Vehicle states and torque control inputs during stabilization of steady-state equilibrium point. The dotted curves correspond to the stabilization of the vehicle model neglecting the suspension dynamics.



(a) (b)

Figure 13: Stabilized vehicle trajectory starting from perturbed unstable steady-state conditions: (a) Case I; (b) Case II.

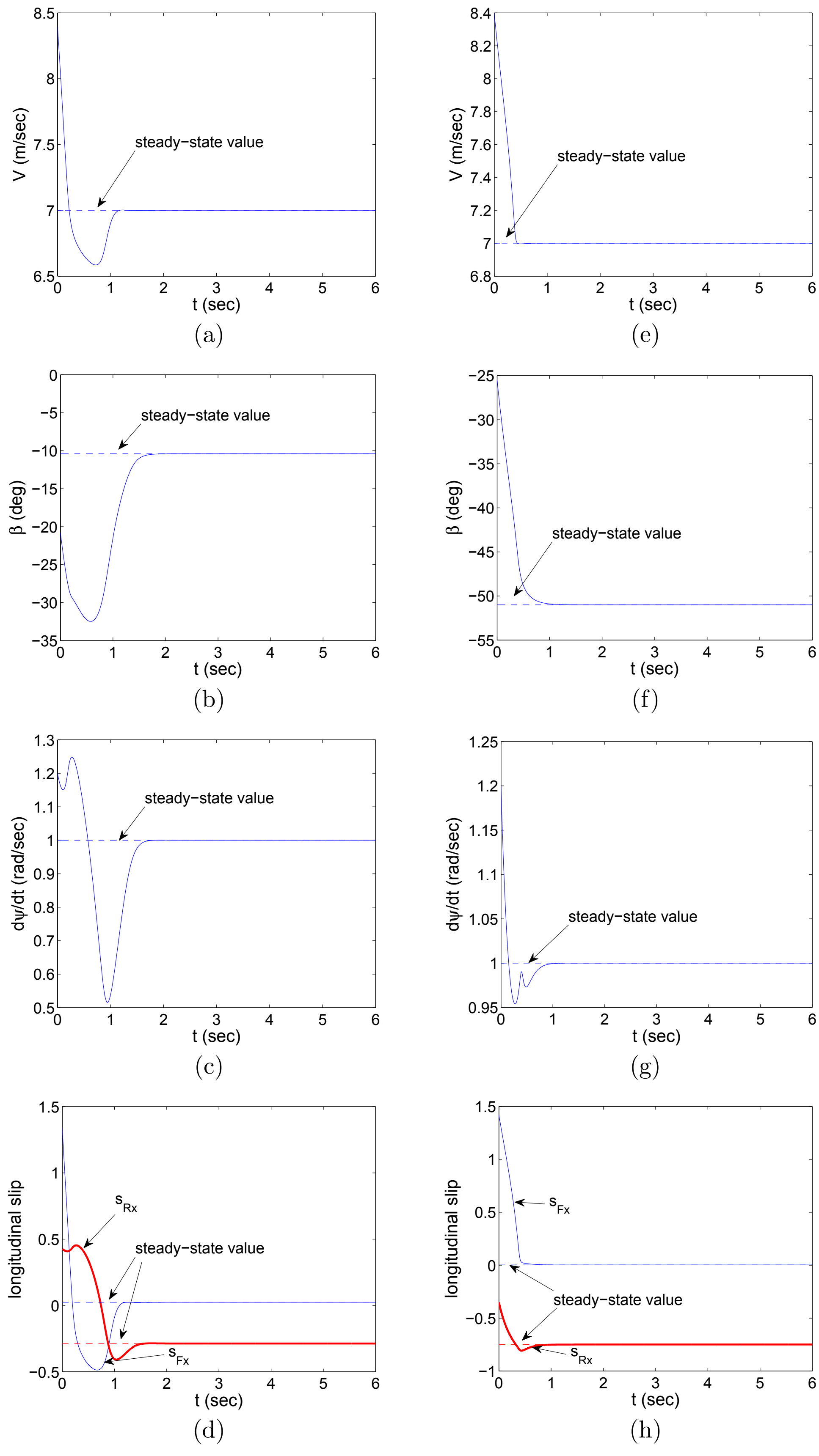


Figure 14: Vehicle states and longitudinal slip inputs: (a) Case I speed; (b) Case I slip angle; (c) Case I yaw rate; (d) Case I front and rear longitudinal slip; (e) Case II speed; (f) Case II slip angle; (g) Case II yaw rate; (h) Case II front and rear longitudinal slip.

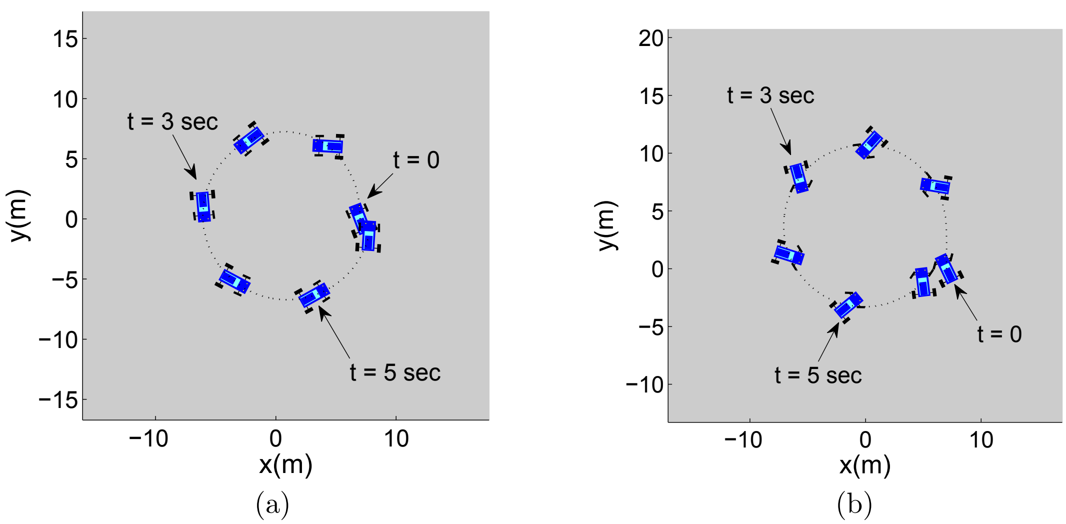


Figure 15: Steady-state cornering stabilization via sliding mode control; (a) Case I and (b) Case II.

Vehicle Posture Control through Aggressive Maneuvering for Mitigation of T-bone Collisions

Crash statistics from the National Highway Traffic Safety Administration (NHTSA) point to a higher occurrence of traumatic head injuries in T-bone collisions, partly due to the fact that today's vehicles most commonly have better frontal impact protection as compared to side impact protection. Even for an unavoidable collision, there is the possibility of mitigating the effects of the collision by applying intelligent control to (at least) one of the vehicles. In this work, we analyze an unavoidable T-bone collision scenario between two vehicles, under the assumption that the intelligent vehicle is mechanically sound, and sufficient road-tire traction exists to allow the execution of the proposed maneuver.

The maneuver involves a segment of maximum straight-line braking, followed by a rapid yaw rotation that brings the longitudinal axes of the two vehicles into a near parallel alignment. Such a relative pre-impact orientation will allow the residual kinetic energy of the collision to be distributed over a larger surface area, thus mitigating the effects of the collision. In this work, we consider only the second segment of the maneuver, involving the rapid yaw rotation.

The execution of the proposed maneuver is facilitated by Torque Vectoring (TV) technology, which allows the creation of a "direct" yawing moment, in addition to that generated by front-wheel steering inputs. Torque Vectoring is a technology that seeks to combine the more traditional Differential Braking (DB) and Active Differential (AD) technologies into a single device that can impact a pure yaw rotation on the vehicle. More details about TV are discussed in the next section.

Torque Vectoring (TV) technology, described as "left-right torque vectoring" uses the concepts of Differential Braking (DB) and Active Differential (AD) in tandem, to vector torque between the left and right wheels, such that a braking force is generated on one side while a tractive (driving) force of the same magnitude is generated on the other. The result is a direct yawing moment on the vehicle.

We use a "single-track" model to represent the vehicle dynamics. Owing to the large vehicle rotations the tires operate in their nonlinear region. The maximum force a tire can extract from the ground is finite, and the maximum longitudinal and lateral forces that can be achieved at a given time are not mutually independent. These constraints are represented by the so-called "friction circle. In this work, a representation of the friction circle is utilized as follows:

$$F_{x*} \leq \mu F_{z*}, \qquad * = f, r, \tag{1a}$$

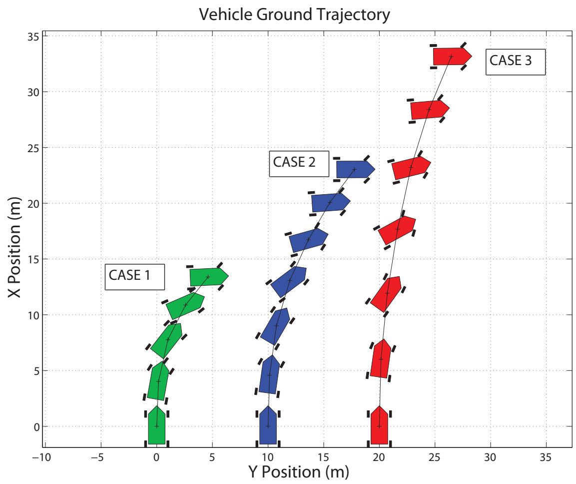
$$F_{y*}^{\max} = \sqrt{(\mu F_{z*})^2 - F_{x*}^2}, \qquad * = f, r. \tag{1b}$$

In the above formulas F_{xf} and F_{xr} are the longitudinal front and rear tire forces, F_{yf} and F_{yr} are the lateral front and rear tire forces, and F_{zf} and F_{zr} are the normal forces at the front and rear axles. The conditions (1) together enforce the friction circle constraint. The proposed rotation maneuver is performed subject to the following assumptions.

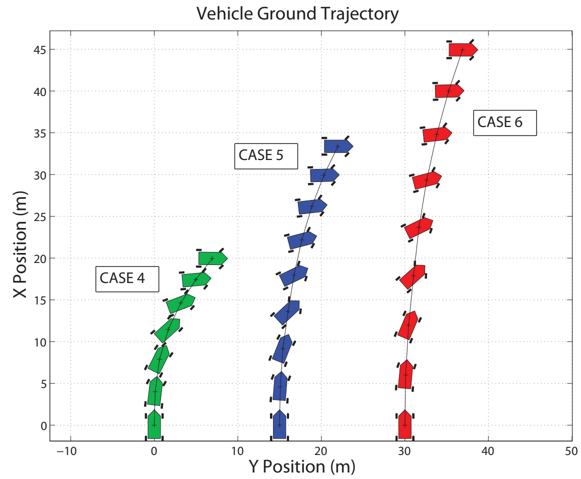
1. DB and AD act only on the rear axle.
2. The combined effect of DB and AD is to generate equal and opposite forces on the rear-left (RL) and rear-right (RR) tires, similarly, to the TV concept.
3. The driving and braking forces sent to the front and rear axle are distributed in the ratio $(1 - \gamma) : \gamma$, where $\gamma \in [0, 1]$.
4. The RL and RR tires see the same lateral slip angle.

Using optimal control theory, several minimum-time trajectories were generated in dry and wet asphalt conditions. The corresponding trajectories are shown in Fig. 16. The optimality of the obtained solutions was verified from the time histories of the Hamiltonian and the co-states of the problem. Conformity with the problem constraints was used to ensure control feasibility.

The reachability of the optimal state trajectory computed by the optimal control solver was verified by running a MATLAB validation model of the vehicle with the optimal control inputs, thus validating the optimal solution.



(a) Dry Asphalt Case.



(b) Dry Asphalt Case.

Figure 16: Ground minimum-time trajectories.

The results obtained, in conjunction with accepted values of required stopping distances from various initial speeds, allow a decision-making strategy to be superimposed on the collision mitigation/avoidance problem, where the recommended action depends on the distance between the intelligent vehicle and the second vehicle, when the latter is sighted and classified as a collision threat.

Table 2 shows the stopping distances required from initial speeds of the three cases of the dry asphalt case (40 km/h (Case 1), 55 Km/h (Case 2), and 72 Km/h (Case 3)). These figures are from the Virginia Code - Tables of Speed and Stopping Distances (46.2-880), and apply to vehicles in good condition on a level, dry road free from loose material. The same table also shows the X-distance traversed during the rotation for each of Cases 1, 2, and 3. It is clear that in each case the X-distance traversed during the aggressive rotation is less than the distance required to brake to a full stop in a straight line. This results in the creation of an "option window" (Zone Z-2 in Fig. 17), such that if the second vehicle is spotted within this window, a successful 90 deg rotation is possible, although braking to a full stop using straight-line braking is not.

In addition to zone Z-2, Table 3 shows the recommended actions for the other two zones which arise, namely Z-1 and Z-3. It should be noted that zone Z-1 allows neither successful braking nor successful rotation, while Z-3 poses no real threat as simple straight-line braking will suffice. Figure 17 also shows the relative positions and lengths of the zones for the three speeds considered.

Table 2: Option Windows for Cases 1, 2, and 3

Case	Speed (Km/h)	Stopping dist. (m)	Rotation dist. (m)	Option Window (m)
1	40	26	15	11
2	55	41	24	17
3	72	60	35	25

In short, results are presented for an optimal aggressive maneuver aimed at mitigating the effect of an unavoidable collision between two vehicles at a traffic intersection. Differential

Table 3: Recommended Actions for Cases 1, 2, and 3

Zone	Braking to stop	90 deg. Rotation	Recommended Action
Z-1	Impossible	Impossible	Rotate
Z-2	Impossible	Possible	Rotate
Z-3	Possible	Possible	Brake

Braking (DB) and Active Differential (AD) technologies have been used in a novel manner to generate a direct yawing moment on the vehicle, especially when combined in tandem to as in the Torque Vectoring (TV) concept. The aggressive maneuver has been posed as an optimal control problem and solved numerically, and the solution has been validated using a nonlinear model of the vehicle. Maneuver simulations were performed with different initial speeds and friction coefficients, representing distinct weather and traffic situations. The creation of an "option zone" due to the performance of the aggressive rotation has been described and explained. The variation of this zone between three initial speeds has also been analyzed.

A Framework for Multi-loop Interactive Control Motivated by Driver-in-the-loop Vehicle Dynamics Controls

Today's vehicles are equipped with many electronic devices. Those devices improve vehicle performance, comfort and safety. While human-centered vehicle design is increasing the utility of electronic devices, the interaction between driver and electronic devices remains critical for the further advance of vehicular systems. Correct decision and action on behalf of the driver can increase the effectiveness of the electronic devices and minimize traffic accidents. On the other hand, because of the possibility of driver error (such as misjudgment, inattention, distraction, or incorrect response to an emergency, etc.), which are the cause of 45% to 75% of roadway collisions, electronic devices need to be more intelligent. We need to investigate the opportunities to develop systems that can differentiate different scenarios and intervene accordingly.

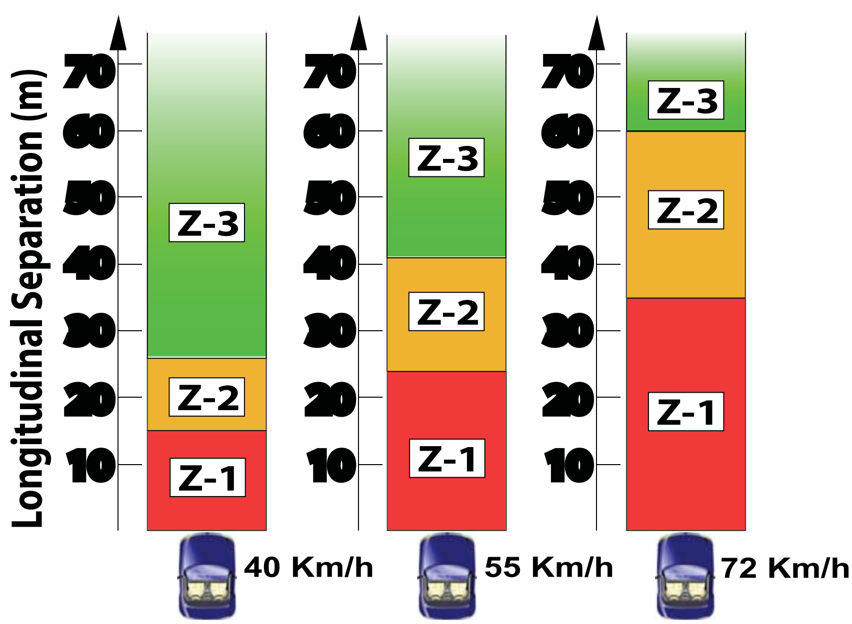


Figure 17: Decision making options.

In this work we have investigated the combined vehicle/driver system using a multi-loop framework. Each loop has its own sensing, decision making and actuation. One of the loops is the primary loop (e.g. the driver control loop) which determines the system goal with a continuous activation. All the other loops support the primary loop, namely, assist the primary loop to achieve a control performance goal. Although the output of the controller in the primary loop (primary controller) can be observed by the controllers in the secondary loops (secondary controllers), the control structure and parameters of the primary controller are unknown. Such uncertainties in the primary controller corresponds to the unpredictable behavior of a human driver, which might be affected by a number of factors that are not observed by the secondary controllers, e.g. driver's physical, cognitive, or psychological states.

The control schemes considered here are rather non-traditional, including *passive control*, *semi-autonomous control*, and *autonomous control*. The proposed approach integrates discrete and continuous states and integrates passive and active schemes. Such an approach is a non-traditional "hybrid approach" for system identification, situation awareness and control design.

One possible architecture to implement this control scheme is the so-called Driver Management System (DMS) shown in Fig. 18. An essential part of the DMS is the Intelligent Personal Minder (IPM) system. Generally speaking, the intelligence computed for the IPM system can be sent to warn or to advise a driver through various devices including a haptic pedal, a heads-up-display, an audio warning device, etc. The IPM utilizes intelligence inferred from vehicle states, measured signals, and the other computed variables used for active safety and vehicle control purposes. The onboard computing resources, algorithms, and sensors used to deduce such intelligence exist in current electronic stability control systems.

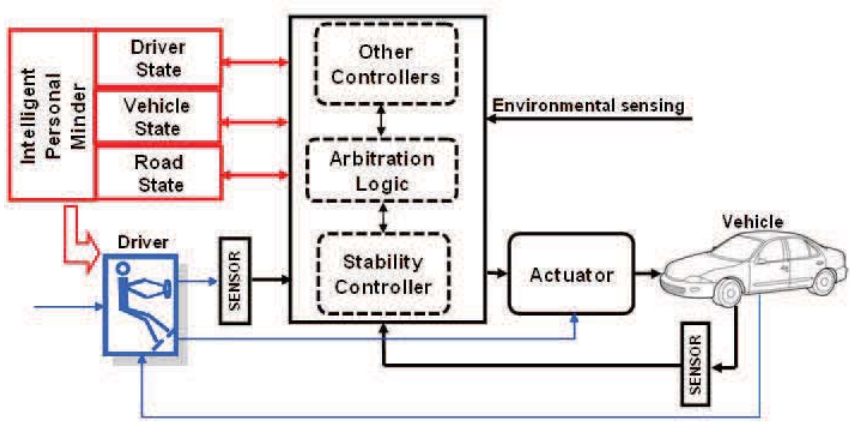


Figure 18: The block diagram of a vehicle control system including an intelligent personal minder (IPM).

Part of the IMP is the Handling Limit Minder (HLM) which determines how close the current driving condition is to the handling limit. Generally speaking, accurate determination of the handling limit conditions would involve direct measurements of road and tire characteristics or very intensive information from many related variables if direct measurements are not available. When the motion variables deviate from their reference values by a certain amount (e.g., beyond certain deadbands), the ESC systems will start to compute differential braking control command(s) and determine control wheel(s). The corresponding brake pressure(s) is then sent to the control wheel(s) to stabilize the vehicle. The starting point of the ESC activation can be thought of as the beginning of the handling limit.

Based on the handling limits we can define the handling limit *margin*, (h) which shows how close is the vehicle to its handling limits. Different vehicles and also different drivers have different handling limit margins. The handling *risk* factor (HRF) can be obtained by the handling limit factor from $r = 1 - h$. The handling risk factor is minimal ($r = 0$) when the final handling limit margin h is maximal ($h = 1$) and vice versa. The HRF is further used to develop a probabilistic model describing different categories of driving styles which are reflected by the current driving conditions with respect to the handling limit.

Generally speaking, a cautious driver usually drives without frequent aggressiveness, i.e., fast changes of steering, speed, and accelerations. Hence it is reasonable to characterize a cautious driver as the one who constantly avoids using extreme driving inputs and getting close to the maximal handling risk. An average driver likely exhibits a higher level of HRF than a cautious driver does. An expert driver might be more skillful in controlling the vehicle, i.e., he can drive with a relatively high level of HRF for a long duration without having the vehicle pass the maximal handling limit. A reckless driver exhibits a careless handling behavior which is unpredictable and could induce fast changes. The reckless driver is expected to drive with a handling risk factor that might approach the maximum ($r = 1$) very briefly from time to time, thus causing frequent triggering of the related safety systems. Figure 19 shows the relationship between the degrees of membership for each of those categories of drivers and the HRF. Figure 20 shows the handling limit margin and the probability of the driver's driving style for two separate vehicle test data.

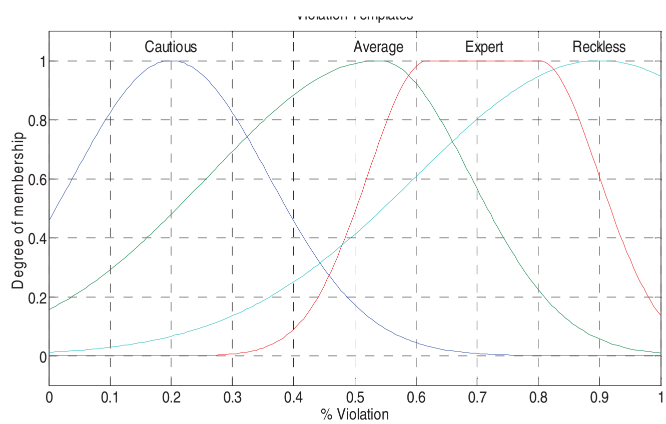
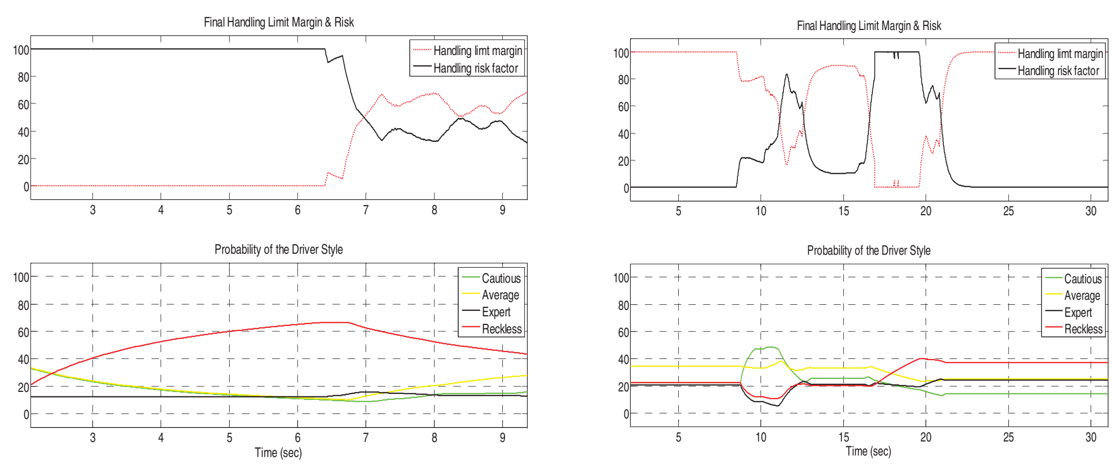


Figure 19: Membership functions characterizing the four driver categories based on the handling risk factor.



(a) (b)

Figure 20: Membership functions characterizing the four driver categories based on the handling risk factor.