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June 8, 2015

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Subject: Comments on CPSC NPR for ROVs

Background

My name is Thomas D. Gillespie. I am a mechanical engineer with a B.S., M.S. and Ph.D. in mechanical engineering. My credentials are further documented in the CV attached (Exhibit A) including a list of over 100 technical publications and several books I have authored.

I have been involved in the design, development and testing of motor vehicles throughout my professional career. My experiences relevant to the matter at hand include:

1) Testing off-road equipment at the U.S. Armor and Engineer Board while serving in the U.S. Army Corps of Engineers.
2) Work as a design analysis and test engineer at Ford Motor Company.
3) Conducting research at the University of Michigan Transportation Research Institute (UMTRI) on modeling and simulation of motor vehicles.
4) Teaching university courses in Mechanical Engineering on Machine Design, Automotive Engineering and Integrated Vehicle Systems Design.
5) Teaching 3-day short courses in vehicle dynamics based on my book, *Fundamentals of Vehicle Dynamics*.
6) Co-teaching 4-day short courses in Dynamics of Heavy Trucks at the University of Michigan campus and in other venues.

As a result I have accumulated 50 years of professional experience in the dynamics of both passenger cars and commercial vehicles. While most of this has been involved with on-road dynamics, over the years I have had some personal experience with recreational off-road driving of motorcycles and 3-wheel ATVs.

At ROHVA's request, I reviewed the Notice of Proposed Rule (NPR) relating to recreational off-road vehicles (ROVs), paying particular attention to those statements and proposals for which my book was cited as authority. I also participated in a day-long familiarization session involving four different models of ROVs. I both drove and rode in these ROVs over dry, loose gravel trails of gradients and surface roughness so severe as to be impassable to typical passenger cars and came to appreciate the mobility capability provided to users by these vehicles. Individual terrain features varied from 5-10" in height, particularly "washaway" features caused by running water as well as deep ruts and large rocks embedded in the surface. Estimated gradients ranged up to a slope of around 50% both up and downhill. I also drove these vehicles on a dirt surface through a series of defined maneuvers, including circles and slalom type turns.

As a result of experiencing four very different vehicles on a wide range of terrain and making a number of detailed enquiries, it is clear to me that the fundamental dynamics of these vehicles gives them good off-road mobility, which is a key attribute. It is also clear that there are significant differences in the dynamics of off-road versus on-road vehicles, as well as differences in the driving techniques required to operate in such dissimilar environments. Considering that ROVs are designed specifically for performance on rough and variable off-road terrain it is not clear that on-road vehicle dynamics principles are directly applicable to ROVs operating on off-road surfaces. Recognizing that this is a fundamental assumption in the NPR that could be wrong, the principles of on-road vehicle dynamics proposed in the NPR should first be carefully and thoroughly tested with off-road vehicles in an off-road environment to establish their validity for achieving the goals of the CPSC.

A. Vehicle Design for On- Versus Off-Road

The dynamics of driving cars on paved, public highways is distinctively different than that of driving recreational vehicles off-road. It is not only the differences between paved and unpaved roads with distinctly different friction properties, but also the driving style in each environment.

Driving vehicles on the public roads is for the most part oriented toward the utilitarian function of traveling to a destination. While we put engineering effort into giving highway vehicles good performance in acceleration, braking and handling, exhibiting a highly dynamic driving style on public highways is discouraged by law enforcement. Further, the public road system is purposely designed to avoid the need for high level dynamics by maintaining controlled speeds and designing for only modest levels of lateral acceleration (e.g., designing curves for no more than 0.15g per recommendations of the American Association of State Highway and Transportation Officials in their Policy on Geometric Design of Highways and Streets). Because of the presence and proximity of other traffic, drivers are discouraged from using the full envelope of dynamic performance available. The smooth surfaces and absence of contamination mean that the available friction is high – typically about 0.8g in dry conditions and remaining above 0.4g even in wet conditions. This contrasts with recreational off-road driving where dirt surfaces give an available friction range from 0.2g-0.5g. The resulting dynamic motions of the vehicles require more driver input and the environment allows them to be driven much more dynamically.

It should be noted that my book, *Fundamentals of Vehicle Dynamics*, was written for the audience of engineers designing modern day passenger cars and trucks that are used by casual drivers on the public road system, not off-road. It does not address design for high performance vehicles (i.e., race cars) nor for off-road vehicles like ROVs. Engineering principles applicable to these vehicles are left to other authors (e.g., William & Doug Milliken, *Race Car Dynamics*, and others).

The design of vehicles for on-road performance has become refined by the automotive community over the past century and could be considered a well-understood technology. However the intended use and functionality expected from ROVs is distinctively different from the on-road behavior of passenger cars. Hence, reliance on my work with on-road vehicle dynamics as a basis for CPSC to establish ROV off-road handling and stability requirements in the NPR warrants a careful review and reconsideration due to the significant issues raised below.

B. Significance of Steady-State Understeer Gradient

The concept of understeer gradient used in *Fundamentals of Vehicle Dynamics* is a vehicle property that summarizes the influence of vehicle, suspensions, steering and tires on directional behavior. It is not a single value but varies continuously with the vehicle's operating state (e.g., in acceleration, braking, cornering and road surface properties).

The understeer gradient is of interest to automotive engineers because it is a measure characterizing directional responsiveness. It is directly related to the cornering compliance of the front and rear axles, quantified by the sideslip angle per unit of lateral acceleration (e.g., degrees per "g") at each axle. The sideslip angle results from cornering compliance of the tires along with numerous suspension and steering contributions as detailed in Chapter 6 of *Fundamentals of Vehicle Dynamics.* The performance obtained is very dependent on tire vertical loads and orientation as affected by front-to-rear and side-to-side weight distributions, lateral acceleration and vehicle roll angle, as well as variations in road elevation.

As a consequence the understeer gradient is only practical to quantify responsiveness in a quasi-steady state operating state as reflected in the ISO and SAE testing procedures for constant radius, constant velocity, and constant steer angle tests. In quasi-steady state driving it is fairly easy to observe relationships between understeer and vehicle behavior. In general, understeer implies a vehicle is less responsive to steering inputs, while oversteer is more responsive.

As was pointed out by CPSC, a vehicle with oversteer will have a critical speed above which the vehicle becomes unstable. While this is true, it does not mean that every vehicle that is operating in an oversteer condition is above its critical speed and unstable. This point is made on page 205 of *Fundamentals of Vehicle Dynamics* where it states that "An oversteer vehicle can be driven at speeds less than the critical, but becomes unstable at and above the critical speed." Similarly, it is incorrect to assume that every vehicle with oversteer is capable of even reaching critical speed (that speed at which the vehicle would become dynamically unstable). Put simply, oversteer is not synonymous with dynamic instability.

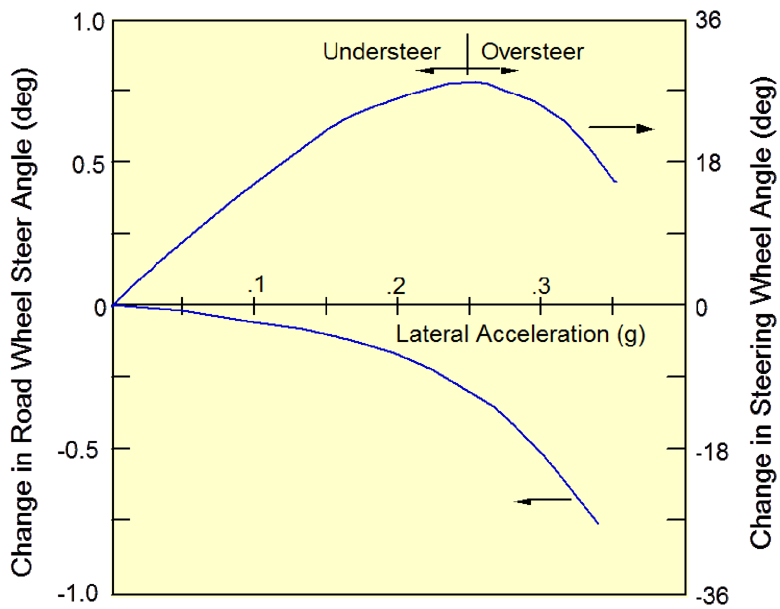
The understeer level on a typical passenger car or light truck in a lightly loaded state is often on the order of 3 to 5 degrees per "g." This is to provide a margin to deal with the reduction of understeer that occurs when load is added to the vehicle, when the vehicle is braking, when tire pressures are not properly maintained, or when a rear tire blowout occurs. On the other hand, because sports cars do not have to undergo as much load change as passenger cars and more responsive handling is desired, they typically have lower levels of understeer – on the order of 1 to 2 degrees per "g."

The effect of understeer level on responsiveness can be quantified by many metrics. One of the most intuitive is lateral acceleration gain, which is the amount of lateral acceleration, a_y, per unit of steer input, δ, at a given speed. The lateral acceleration gain is given by the equation below:

$$\frac{a_y}{\delta} = \frac{\dfrac{V^2}{57.3L \cdot g_c}}{1 + \dfrac{K \cdot V^2}{57.3L \cdot g_c}}$$

Where: K = Understeer gradient
δ = Front wheel steer angle
V = Forward velocity
L = Wheelbase
V = Velocity
g_c = Gravitational constant

As long as the denominator is positive the lateral acceleration gain is finite and the vehicle is controllable. Hence even though K is negative (oversteer) the vehicle is drivable and does not exhibit instability. This is illustrated by Figure 8.19 in *Fundamentals of Vehicle Dynamics* showing constant-radius understeer tests by the author on a truck. The steering wheel angle change as a function of lateral acceleration shown in the top half of the plot is the primary interest.



The upward slope of the top plot indicates that the vehicle exhibited understeer at the steering wheel, up to 0.25g where it transitions to oversteer. (This was typical behavior of trucks.) Note however, that the plot continues up to 0.35g of lateral acceleration which is only possible because the vehicle is still controllable, even though in an oversteer condition. Thus using the transition to oversteer as a criterion for unacceptable dynamic behavior is overly conservative and technically not warranted.

The ability to drive oversteer vehicles was also demonstrated by the SEA tests of ROVs for the CPSC. The plot of steering gradient slopes shown in Figure 6 of the CPSC Safety Standard for Recreational Off-Highway Vehicles (ROVs); Proposed Rules published in the Federal Register Vol. 79 No. 223, November 19, 2014, show test results from ROVs which were driven on a circle in an oversteer condition to lateral accelerations as high as 0.5g.

The point to be made is that **oversteer vehicles can be driven safely as long as they are below critical speed** because they have a finite lateral acceleration rate gain – which is to say they simply adjust to a new, slightly tighter turn radius. When the driver is providing closed-loop steering feedback to maintain the vehicle on the intended path, the transition to oversteer is marked not by some immediate and critical correction but by a slight relaxation in steering input to maintain the desired line over the ground. Indeed the onset of the oversteer condition is so subtle that it requires careful experimentation to discern it because it is not obvious to the driver. That is, the vehicle is stable when directional response measured by driving at various speeds on a constant radius circle with closed-loop steering control can settle to some steady state value. The very existence of a steady state condition proves convergence regardless of the details of the test procedure. **The appropriate engineering inquiry, therefore, is whether the vehicle is capable of reaching critical speed (i.e., displaying instability) within the intended or foreseeable use of the vehicle.**

C. Transient Dynamics

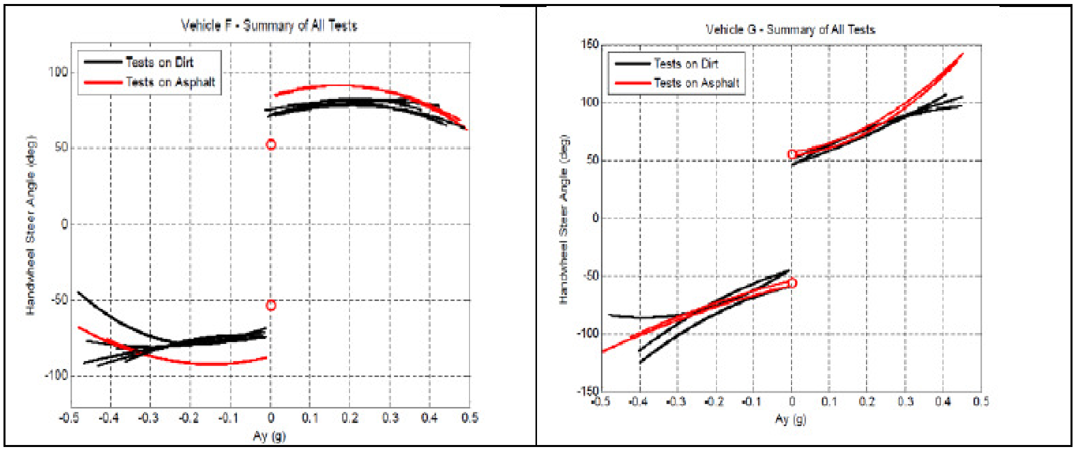
It is apparent that a substantial part of the functional utility provided by ROVs is off-road mobility. The most obvious difference with ROVs operating in an off-road environment is the continuous maneuvering and steering of the vehicle required to follow paths and trails. This means the ROV rarely if ever really experiences a "steady state" cornering condition – nor even the straight line steady state condition. Therefore regulating their performance characteristics by steady-state behavior on pavements is unaligned with these vehicles' most common operating condition and of highly questionable validity.

For example, it appears that the CPSC commissioned only limited testing on the disparity between ROV behavior on pavement and ROV behavior on surfaces such as dirt, sand, gravel, and other terrain where the vehicles are designed for operation. But even that limited testing revealed variances between oversteer and understeer depending on the surface type and run.

Specifically, SEA tested only two ROV models (Vehicles F and G) using both asphalt and dirt circle tests. It is unclear why only these two specific vehicles were chosen for this testing. With respect to Vehicle F, SEA conducted six sets of circle tests on dirt (each set involving one run in the clockwise direction and one run in the counter-clockwise direction) and two sets of circle tests on asphalt. With respect to Vehicle G, SEA conducted three sets of tests on dirt and two sets on asphalt.

Based on these runs, SEA reported that the testing results for both vehicles on asphalt were consistent, with Vehicle F exhibiting oversteer and Vehicle G exhibiting understeer. However, the testing results for both vehicles on dirt indicated that the steering gradients of the vehicles varied between understeer and oversteer in different runs. As reported by SEA, *Circle Testing of Two Recreational Off-Highway Vehicles on a Dirt Surface*, June 2013, at page 4:

> [T]he six sets of tests [for Vehicle F (which consistently exhibited oversteer on asphalt)] conducted on dirt indicate varying results. Some of the curve fit trends indicate understeer characteristics and some of them indicate transition to oversteer, like the tests on asphalt did. * * * [T]he three sets of test [for Vehicle G (which consistently exhibited understeer on asphalt)] conducted on dirt indicate varying results. Some of the curve fit trends indicate transition to oversteer and some of them indicate understeer at all lateral levels, like the tests on asphalt did.



In reporting these variances, SEA attributed the lack of repeatability on the dirt surface to "variations in the relatively large steering corrections for the tests," as well as greater "cornering forces" at the front tires encountered on dirt as opposed to asphalt. SEA, Ltd., "Circle Testing of Two Recreational Off-Highway Vehicles on a Dirt Surface," at 5-6 (June 2013), www.cpsc.gov/Global/Research-and-Statistics/Technical-Reports/Sports-and-Recreation/ATV-ROV/ROVCircleTesting.pdf (prepared for CPSC). While these may be among the factors affecting the variations revealed in this limited SEA testing, it is apparent that the steering gradient variation resulting from the dirt surface is significant. The same variations may be even greater on other off-road surfaces, such as rocky terrain, sand, or gravel. In all events, these kind of variations indicate that the on-asphalt steering characteristics of an ROV are not reliably predictive of its off-road steering characteristics (i.e., in the environments where it is designed for operation).

More specifically, looking at the terrain and the tires, it is obvious that surface roughness commonly encountered by ROVs causes the tires to briefly lose contact with the surface. This is a very different condition from passenger cars, where tires rarely, if ever, lose contact with the road. Intermittent loss of contact with the surface effectively reduces the friction coupling and the surface appears more slippery than it actually is. Consequently, one of the significant challenges for ROV designers is to maintain traction coupling with the surface in order to develop the forces needed for propelling and maneuvering the vehicle.

This intermittent contact places great emphasis on the ROV driveline and the coupling between wheels and the surface. Even on comparatively level ground with good traction, it is desirable to avoid momentary spin up of individual wheels that interrupts propulsion and causes disturbance to the vehicle motion when it regains contact with the ground.

Another clear difference between ROVs and passenger cars is that ROVs may spend much of their time operating in a region of non-linear dynamic behavior arising from soft terrain. Yielding of terrain under the tires modifies the path of the vehicle and may leave obvious ruts behind the front wheels that interact with tracking of the rear wheels. Developing ROVs to accommodate these driving conditions is in marked contrast to that of passenger cars that operate on rigid, paved road surfaces.

All of these differences mean that designing ROVs to meet smooth-road measures of handling performance is a speculative approach that does not ensure a vehicle with acceptable off-road performance. It is thus an unproven (and potentially unsound) basis for setting mandatory vehicle design and performance requirements.

D. CPSC Vehicle Handling Requirements

In the NPR published on November 19, 2014 the CPSC is proposing a metric that would prohibit sale an ROV which transitions to oversteer below 0.5g as measured by the SAE Constant Radius test method on a circle of 100-foot radius on a paved surface.

The criteria for acceptable performance places great emphasis on avoidance of oversteer in a driving environment that is uncommon for ROVs. Placing such importance on steady state SAE oversteer on paved surfaces as an indicator of off-road stability is also speculative and overly simplistic. This is especially true with ROVs because the driver plays a very active role in the vehicle dynamics. Oversteer is not instability, it is simply a vehicle property associated with the current dynamic operating state of the vehicle, which in the test procedure is quasi-steady state driving on a level, paved surface. Though the vehicle may be in oversteer, the driver-vehicle combination may well be stable. It is well recognized that understeer vehicles can transition to oversteer during transient conditions such as severe brake applications because of the weight transfer off of the rear axle. To restrict the vehicle performance envelope to understeer on paved surfaces will potentially compromise the responsiveness that many ROV drivers consider an important contributor to the agility needed for safe off-road operation. The loss in responsiveness reduces the driver's ability to stay on the desired driving path increasing the potential for crashes. This is clearly a questionable basis for setting mandatory vehicle design and performance requirements.

E. Conclusion

In summary, I would like to suggest a need for significant caution regarding the intended regulation of ROV dynamic behavior. **I am concerned that the fairly brief and simple explanation of oversteer presented in my book is insufficient to provide a sound engineering basis for regulating performance as proposed in the NPR**. Restricting the dynamic responsiveness of ROVs in a paved-surface understeer test environment so dissimilar from its normal use cannot be imposed without potential for degrading other unknown aspects of off-road performance. Hence it is far from clear that the design changes that will be required by the regulation will necessarily contribute to a positive influence on ROV design, but may have unintended adverse consequences on vehicle handling, performance, and safety.

Very truly yours,

Thomas D. Gillespie

Thomas D. Gillespie, Ph.D.

Attachments:
CV

THE UNIVERSITY OF MICHIGAN
TRANSPORTATION RESEARCH INSTITUTE

NAME	Thomas D. Gillespie
TITLE	Research Professor Emeritus
EDUCATION	B.S., Mechanical Engineering, Carnegie Institute of Technology, 1961 M.S., Mechanical Engineering, Pennsylvania State University, 1965 Ph.D., Mechanical Engineering, Pennsylvania State University, 1970
RESEARCH INTERESTS	Transportation policy —truck standards and regulations —management of highway systems Transportation safety —motor vehicle braking, handling, and ride —highway roughness and skid-resistance
WORK EXPERIENCE	1998-2006 Research Professor and Adjunct Professor 1988-1998: Director, Great Lakes Center for Truck and Transit Research 1987-1988: Senior Policy Analyst, White House Office of Science and Technology Policy, Executive Office of the President 1976-1987: Research Scientist, UMTRI 1973-1976: Group Leader, Heavy Truck Engrg, Ford Motor Company 1970-1973: Research Assoc., Pennsylvania Transportation Institute 1966-1970: Research Asst. in Mechanical Engineering, Penn State 1964-1966: Project Officer, Armor and Engineer Board, U.S. Army 1963-1964: Engineer, Glass Research Center, PPG Industries

Dr. Gillespie's professional career has been primarily concerned with advanced engineering and research in the automotive and highway areas. From the beginning, his career spanned the breadth of these areas, ranging from applied research at the Pennsylvania State University in pavement friction test methods, to responsibilities as a Project Officer with the U.S. Army Corps of Engineers directing engineering and service tests on new military construction equipment. At Ford, he served as a group leader in development testing of new heavy truck products, as well as, development of analytical methods and computer programs for predicting truck braking, handling, and ride performance. His expertise in the area of road roughness and vehicle dynamic interactions led to consultation with the World Bank directing the international experiment that developed the worldwide standard used for measurement of road roughness.

In 1987-88 Dr. Gillespie served on the White House staff as a Senior Policy Analyst for Dr. William R. Graham, Science Adviser to President Reagan. He later served as a consultant to Dr. Allan Bromley, Science Adviser to President Bush, chairing the Interagency Task Force to develop a National Action Plan on Advanced Superconductivity Research and Development.

On returning to the University, Dr. Gillespie served for ten years as Director of the Great Lakes Center for Truck and Transit Research. His teaching included automotive engineering, vehicle dynamics and vehicle design, offered to university students and industry engineers. He retired from the University in 2006. He now works part time for Mechanical Simulation Corporation, consults, and teaches vehicle dynamics to industry groups.

AWARDS, SOCIETIES:

Fellow, Society of Automotive Engineers
SAE Fellow in the White House Office of Science and Technology Policy
Leader, Interagency Task Force for a National Action Plan on Advanced Superconductivity
L. Ray Buckendale Award (Society of Automotive Engineers)
Forest R. McFarland Award (Society of Automotive Engineers)
Editorial Advisory Board, Journal of Advanced Transportation
Editorial Advisory Board, International Journal of Vehicle Design, Heavy Vehicle Systems
Editorial Board, Journal of Mobility and Vehicle Mechanics
Editorial Board, Journal of Vehicle System Modeling and Testing
Michigan Truck Safety Commission (Former member)
Mesta Machine Company Scholarship, National Science Foundation Traineeship
Phi Kappa Phi, Sigma Xi Honor Societies
Who's Who in America, American Men & Women of Science
Registered Professional Engineer/Pennsylvania (#15412E)
Invited speaker tour of Australia (Australian Road Research Board)
First William Milliken Invited Lecture 2013, American Society of Mechanical Engineers
John Orr Memorial Lecture 2014, South Africa Institution of Mechanical Engineers

COMMITTEES

National Academy of Sciences, Transportation Research Board, Committees for:
Commercial Truck and Bus Safety Synthesis Program
Study of the Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles
Study of Automotive Consumer Information Needs
Review of the 21st Century Truck Partnership

Society of Automotive Engineers
Faculty Adviser, University of Michigan SAE Student Branch
Engineering Education Committee
ABET Relations Committee
Vehicle Dynamics Standards Committee (Chairman)
Government Relations Committee
Membership Grading Committee
Truck and Bus Chassis Committee
Myers Award Committee
Arnold W. Siegel International Transportation Safety Award Committee

Professional Journals
International Journal of Vehicle Design, Editorial Board
International Journal of Vehicle Systems Modeling and Testing, Editorial Board

BOOKS

Fundamentals of Vehicle Dynamics. Society of Automotive Engineers, Warrendale, PA., 1992, 450 p.

Measuring Road Roughness and Its Effects on User Cost and Comfort (co-editor). American Society for Testing and Materials, Special Technical Publication 884, November 1985, 198 p.

Heavy Truck Ride. Thirty-First L. Ray Buckendale Lecture, Society of Automotive Engineers, Special Publication SP-607, February 1985.

The Influence of Roadway Surface Discontinuities on Safety (co-author). A State-of-the-Art Report, Transportation Research Board, Washington, D.C., 1984.

The Mechanics of Heavy-Duty Trucks and Tractor Combinations (co-author). Published by The University of Michigan, Ann Arbor, June 1981, 1017 p.

TEACHING

1985 - 2005: Ford Motor Company, Dearborn, MI – Fundamentals of Vehicle Dynamics
1990 - 2011: General Motors Corporation, Warren, MI – Fundamentals of Vehicle Dynamics
1988 – 2006: University of Michigan, Ann Arbor, MI – Automotive Engineering
2003 – 2005: University of Michigan, Ann Arbor, MI – Integrated Vehicle Systems Design
1982 – 2011: University of Michigan, Ann Arbor, MI – Mechanics of Heavy Duty Trucks (short course)
1992: New Venture Gear Company, East Syracuse, New York – Fundamentals of Vehicle Dynamics
1997: TRW Steering and Suspensions, Detroit, Michigan – Fundamentals of Vehicle Dynamics
1997: Navistar Truck, Fort Wayne, Indiana – Fundamentals of Vehicle Dynamics
1997: ITT Automotive, Detroit, Michigan – Fundamentals of Vehicle Dynamics
1999: Rassini, Southfield, Michigan – Fundamentals of Vehicle Dynamics and Simulation
2000: Bosch Corporation, Detroit, MI – Fundamentals of Vehicle Dynamics
2005: General Motors Corporation, Toluca, Mexico – Fundamentals of Vehicle Dynamics
2006: General Motors Corporation, Toluca, Mexico – Fundamentals of Vehicle Dynamics
2008: BMW Sauber Race Team, Zurich, Switzerland – Fundamentals of Vehicle Dynamics
2008: Suspensys, Caxias do Sul, Brazil – Fundamentals of Vehicle Dynamics
2010: Automotive Research Institute of India, Pune, India – Fundamentals of Vehicle Dynamics
2010: EASi, Bangalore, India – Fundamentals of Vehicle Dynamics
2010: Suspensys, Caxias do Sul, Brazil – Fundamentals of Vehicle Dynamics
2010: SAE Brazil, Sao Paulo, Brazil – Fundamentals of Vehicle Dynamics
2011: General Motors Corporation, Bangalore, India – Fundamentals of Vehicle Dynamics
2011: Ashok Leyland, Chennai, India – Fundamentals of Vehicle Dynamics
2011: Maruti-Suzuki, Delhi, India – Fundamentals of Vehicle Dynamics
2011: ARAI/EASi, Pune, India – Fundamentals of Vehicle Dynamics

PAPERS AND PUBLICATIONS:

"Pavement Surface Characteristics and Their Correlation with Skid Resistance." M.S. Thesis; Published as PSU-PDH Joint Road Friction Program, Report No. 12, June 1965, 100 p.

"An Analytical and Experimental Study of the Influence of Swirl on Choked Nozzle Flow." Ph.D. Thesis, The Pennsylvania State University, December 1970.

"The Control of Thrust and Flow Rate in Choked Nozzles by Vortex Generation." Presented at 2nd IFAC Symposium on Fluids, Prague, June 1971; *Fluidics Quarterly*, Vol. 4, No. 1, January 1972, pp. 50-55.

"A Program for Reducing Variables in the Measurement of Skid Resistance" (co-author). Presented at the ASTM Annual Meeting, Los Angeles, June 1972.

“Measurement Principles Applied to Skid Testing.” (co-author). American Society for Testing and Materials, Symposium on Skid Resistance of Highway Pavements, 1973.

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"Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers" (co-author). University of Michigan, Highway Safety Research Institute, Report No. UM-HSRI-78-18-1/2, 1978, 257 p.

"Analysis of the Rollover Dynamics of Double-Bottom Tankers" (co-author). Society of Automotive Engineers, Paper No. 781065, 1978, 7 p.

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"The Yaw Stability of Tractor-Semitrailers During Cornering" (co-author). The University of Michigan, Highway Safety Research Institute, Report No. UM-HSRI-79-21-1/2/3, 1979, 549 p.

"Truck and Tractor-Trailer Dynamic Response Simulation - Volume 1: Summary Report" (co-author). The University of Michigan, Highway Safety Research Institute, Report No. UM-HSRI-79-85-1, 1979, 22 p.

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