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Report of Findings

Tennessee Titans / Pyro Shows, Inc., Product Evaluation

Claim No: 201905970

Rimkus File No: 100015424

Prepared For:

Tennessee Department of Commerce and Insurance
500 James Robertson Parkway
Davy Crockett Tower, 9th Floor
Nashville, TN 37243

Attention:

Ms. Mary Beth Gribble

Digitally signed by: Gary L VanderMolen
Date: 2019.10.22 14:44:11 -06'00'

Gary L. VanderMolen, M.S., P.E.
TN Engineering Number 117090
Division Manager

October 22, 2019

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Section I
INTRODUCTION

On September 15, 2019, a pyrotechnic incident was reported at the Tennessee Titans football game, just adjacent to the playing field, located at the Nissan Stadium, 1 Titans Way in Nashville, Tennessee. A special effects flame display system which produced flame columns up to approximately 30 feet high, operated by Pyro Shows, Inc. (Pyro Shows), reportedly malfunctioned and caused an uncontrolled fire.

Rimkus Consulting Group, Inc. (Rimkus) was retained to determine the cause of failure. This report was reviewed by Mr. Mark H. Nelson, CFEI, Division Manager.

This report was prepared for the exclusive use of Tennessee Department of Commerce and Insurance and was not intended for any other purpose. Our report was based on the information available to us at this time, as described in the **Basis of Report**. Should additional information become available, we reserve the right to determine the impact, if any, the new information may have on our opinions and conclusions and to revise our opinions and conclusions if necessary and warranted.

Section II
CONCLUSIONS

1. Operation of the Hurricane Giant flame machine was in compliance with National Fire Protection Association (NFPA) Standard 1123, NFPA Standard 1126 and NFPA Standard 160.

2. Signage on the cart sides was determined to be a contributory factor in harboring fugitive fuel and allowing an obstruction to observation underneath the base of the Hurricane Giant.

3. No other operational issues were observed in the use of the Hurricane Giant machine.

4. The heat shield above the burner lacked adequate thermal insulation barriers between the burner unit and the fuel reservoir, a contributory factor in the incident.

5. The hydraulic hose was inadequate in this application. It was not sufficiently protected from external damage and lacked the thermal properties necessary to resist high temperatures. The improper hose specification by the manufacturer was a significant contributory factor leading up to the incident.

6. The fuel reservoir lacked protection from downstream failures, specifically a shutoff valve at the fuel reservoir outlet, rendering the Hurricane Giant machine unreasonably unsafe. Its absence was a pre-existing design defect from the Hurricane Giant manufacturer, the root cause of the uncontrolled fire.

7. A shutoff valve at the fuel reservoir outlet could have been remotely controlled through the DMX controller and synchronized with the pilot shutoff valve.

8. Further protection would be attained by a nitrogen, rather than fuel, pressure relief device in instances of e.g. thermal expansion.

Section III
DISCUSSION

Background

According to Mr. Lansden Hill, Jr., President and CEO, Pyro Shows had used Hansol Hurricane Giant machines for 5 years prior to the incident. The subject machine had been in service approximately 2 years. There were no prior issues with the machine. A low-pressure cutout valve had been added by Pyro Shows, to each nitrogen charge regulator, upstream of the machine, during 2015. All flame machines were reportedly visually inspected before and after each performance. Pyro Shows performed preventative maintenance on all machines once each year.

During the Titans pre-game special effects presentation, cryogenic fog was emitted from the players' tunnel, tips of the crossed swords at the field entrance "gauntlet", and trusses in front of the swords. Just beyond the trusses, in the southeast corner of the stadium, Pyro Shows technicians had placed four special effects flame display systems for the presentation.

Each flame display system consisted of a Hurricane Giant machine and its transport cart, a nitrogen supply cylinder, inverter and batteries, and a tethered DMX controller. Each cart was constructed with integral nitrogen cylinder holders and was enclosed with team-themed signage.

As the players ran through the gauntlet as they were introduced, a Pyro Shows technician used a DMX controller to provide bursts of flames from each of the four flame machines. Each burst of flame was approximately 1 second duration and was repeated every 5 to 8 seconds. All four systems appeared to function properly throughout the performance.

After the performance on the field had concluded, the Pyro Shows technicians disconnected the DMX cables at the controller and were in process of transporting the machines off the field, including shutoff of the nitrogen charge at the tanks and disconnection of the DMX cables at the machines. Two of the machines had been removed from the field when the remaining subject machine fire began (**Photograph 1**). An estimated duration of 30 to 45 seconds had lapsed between shut-off of the pilot, when the DMX cables were disconnected at the controller, and beginning of the machine fire.

The designated fire watch people responded quickly to the fire with Carbon Dioxide (CO2) fire extinguisher, with application within approximately 13 seconds, but the pressurized fuel exceeded the fire extinguisher capabilities (**Photographs 2 and 3**).

The total duration of the fire was timed at about 60 seconds after the liquid fuel was consumed.

Fire retardant tarpaulins were used beneath all the flame effects machines, as required by the National Football League (NFL). Minor damage was sustained to the natural grass turf and a tarpaulin mat used by players enroute between the field and the players' bench (**Photograph 4**). The area of turf damage was estimated at 80 square feet.

Observations

The subject flame (machine), model Hurricane Giant, serial number HS-PM15-76, was manufactured by Hansol FX South Korea, located at 43-4 Sicheong-ro 677, Paltan Myeon, Hwasung-si, Gyeonggi-do, 445-913 South Korea, in 2017 (**Photograph 5**). The machine measured approximately 16.5 inches long by 15.75 inches wide by 24.5 inches high.

The Hurricane Giant consisted of a pilot flame head and a 16-liter fluid fuel reservoir. A small butane canister which provided the fuel for the pilot flame was connected to the

flame head. The fuel reservoir, using Isoparaffinic Hydrocarbon, Isopar G, was pressurized by an upstream external nitrogen gas cylinder, regulated at approximately 240 to 300 pounds per square inch (psi), through a 2.0-millimeter-diameter nozzle. The DMX safety circuit was configured to detect the pilot flame before flame columns could be generated. The pilot controls were equipped with a manually-operated shutoff valve, featuring an E-Stop function (**Photograph 6**).

A hydraulic hose, constructed of a 90-degree crimp fitting for the fuel reservoir and a straight crimp fitting for the flame head, had been routed through an approximately 2-inch-diameter through-hole in the steel base in order to feed the pilot (**Photograph 7**). In its re-solidified resting state, the hose passed through the hole within 3/8 inches.

No hose protection, such as a guard spring or insulation, was observed around the hose. The hose was badly burned.

The hydraulic hose was NITTA part number 3130-06, constructed of a nylon core tube, woven synthetic fiber reinforcement, and a black polyurethane cover. Its inside diameter was specified at 0.375 inches. Its outside diameter was specified at 0.635 inches. The maximum working pressure was rated at 2,600 pounds per square inch (psi). The working temperature range was specified from -40 degrees Fahrenheit (º F) to 212º F.

The Hurricane Giant was covered with soot. Severe oxidation was observed on the base interior side opposite the hose drop fitting (**Photograph 8**).

The Hurricane Giant was installed on a steel frame and rubber-wheeled cart (**Photograph 9**). The cart, including the side panels, was specified and built by Pyro Shows. The floor was stipulated by the NFL. Appliques for the side panels were provided by the Tennessee Titans.

The cart outside dimensions measured approximately 49.5 inches long by 22.0 inches wide by 41 inches high. The four caster wheels elevated the solid cart floor

approximately 12.5 inches from the ground. Little damage was observed to the cart and the contained batteries, inverter, and integral nitrogen cylinder holders.

Aluminum signage had covered the four sides of the cart. The signage area, adjacent to the machine, sustained warpage and melting from the fire (**Photograph 10**).

On the date of the incident, the temperature high for the Nashville area was 96 ºF. The maximum wind speed was recorded as 8 miles per hour (mph). However, as observed in the incident video, winds were quite strong in the stadium.

Ambient temperatures during the October 2, 2019, demonstration approached 97º F. The surface temperature of the fuel reservoir, in the stadium parking lot, was 101º F. The winds were mild.

After five 1-second flame bursts every 5 to 8 seconds, the burner heat shield temperature exceeded 161º F. The fuel reservoir surface temperature reached 143º F.

Analysis

In the use of fireworks, any composition or device for the purpose of producing a visible or an audible effect for entertainment purposes by combustion, deflagration, or detonation as defined by the NFPA are defined in NFPA Standard 1123. Regarding flame effects, the combustion of flammable solids, liquids, or gases to produce thermal, physical, visual, or audible phenomena before an audience are as defined in NFPA Standard 160.

NFPA 1123 and 160 both required the minimum of two Class-A and two Class-BC fire extinguishers present during pyrotechnic shows or shows involving flame effects. The standards did allow for the authority having jurisdiction (AHJ) to require additional extinguishers. According to the fireworks application packet that was submitted, the AHJ approved the amount and type of extinguishers listed in the packet. Both standards listed requirements for operators and assistants. Neither standard addressed supplemental personnel provided by the sponsor for fire watch or suppression. The

response by the supplemental personnel during the fire event was sufficient; however, the fire had progressed past its incipient stage when it became “fuel-fed”.

Operation of the Hurricane Giant flame machine was in compliance with NFPA Standard 1123. Operation of the flame machine was in compliance with NFPA Standard 1126. Operation of the flame machine was in compliance with NFPA Standard 160.

The badly burned hydraulic hose was consistent with the source of the fuel. The ignition source was consistent with a small initial hose leak to which the pilot flame could have migrated and sustained after the pilot had been shut off. The leak of fuel became larger when the hose further deteriorated as the fire progressed

The relatively sharp edge of the through-hole in the steel base was consistent with a source of possible hose abrasion until the hose failed. The hose was not protected, such as with a guard spring or insulation. The NITTA “Linemate” catalog states that “Pressure on hose products could cause interference with surrounding parts on which no interference exists before the pressure is applied. Please handle appropriately e.g. introducing guard parts.”

Hydraulic hose typically shortens under pressurization. This shortening could have reduced the hose-to-hole clearance during operation, consistent with interference and conducive to abrasion.

The Hurricane Giant was specified at 360 pounds per square inch (psi). The maximum working pressure of the hydraulic hose was rated at 2,600 psi, well beyond the operating pressure in this application.

The hydraulic hose, with a specified working temperature range of -40 to 212º F, would have approached, if not exceeded, the maximum temperature limit during heavy duty usage. Internal heating of the hose from hot fuel could not be eliminated as a contributing factor in deterioration of the hose.

The operators did not visually check for any flames/smoke immediately after the burner pilot was shut off, hindered by signage on the cart sides that was an obstruction to observation. This was considered as contributory factor in not allowing early detection underneath the base of the machine. The enclosed cart also enabled the harboring of fugitive fuel in the early stages of fugitive fuel.

The Pyro Shows and the Pyro Shows display technicians, or operators, were the responsible company and licensed personnel for the operation and safety of displays as contracted by the Titans, the sponsoring organization. All display operators held valid pyrotechnics license from the state of Tennessee. No operational issues, other than the obstructed view of any flames/smoke immediately after the burner pilot was shut off, were observed in the use of the Hurricane Giant machine.

The heat shield on the burner head, located beside the burner, extended above the burner by approximately 1 inch. The Hurricane Giant lacked adequate thermal insulation barriers between the burner unit and the fuel reservoir. The Hurricane Giant lacked adequate thermal insulation barriers between the burner unit and the machine controls.

The hydraulic hose was determined to be inadequate in this application. It was not sufficiently protected from external damage, such as from the sharp edge of the base through-hole, a possibly significant contributor leading up to the incident. It also lacked the thermal properties necessary to resist high temperatures, also a possibly significant contributor leading up to the incident. This fluid conductor could have been constructed from hard piping instead of a flexible hose and bulkheaded through the machine base.

The Hurricane Giant was designed with a normally-closed fuel pressure relief valve, limiting pressures to a maximum of approximately 500 psi. This burner unit valve relieved upstream from the fuel discharge nozzle, thus allowing an unintended fuel source. No indication was determined that the machine failed from over-pressurization of its fluid control components. In its current state, the hose might have provided some compliance for the pressurized fuel. However, the integrity of fuel reservoir, and the fuel

delivery conductors, would benefit from a nitrogen pressure relief protection device for protection during e.g. thermal expansion, as well as eliminating an unintended fuel source.

The fuel reservoir lacked protection from downstream failures, such as a hose or valve failure, rendering the machine unreasonably unsafe. The circuitry should have included a shutoff valve at the fuel reservoir outlet. The absence of an (automatic) shutoff valve was determined to be a pre-existing design defect from the manufacturer, the root cause of the uncontrolled fire.

A shutoff valve at the fuel reservoir outlet could have been remotely controlled through the DMX controller and synchronized with the pilot shutoff valve. Such a safety device would have prevented the subject incident after an otherwise apparently normal operation. This device could also prevent or contain any uncontrolled fuel issue before and during normal operation.

The low-pressure cutout valve, upstream from the Hurricane Giant machine at the nitrogen charge regulator, was determined to have no contribution in the incident.

No indication was determined that the fire started from static electricity as the ignition source. Nonetheless, an initial uncontrolled fuel source would also have been required for the fire to begin after the machine was shut down, such as from the leaking hose, a contributory factor in this incident.

Section IV
BASIS OF REPORT

1. On October 1, 2019, Gary VanderMolen, M.S., P.E., inspected the subject flame display machine at the Pyro Shows, Inc. (Pyro Shows) facility, located at 115 North 1st Street in LaFollette, Tennessee.

2. On October 2, 2019, Mr. VanderMolen and Mr. John Farill, IAAI-CFI (V), NAFI-CFEI, IAMI-CMI, inspected the involved cart and four exemplars at the Nissan facility, located at M1 Titans Way in Nashville, Tennessee. A demonstration on the machine operation of an exemplar was also provided that day.

3. Mr. Lansden Hill, President and CEO, Pyro Shows, Inc., was interviewed during the October 1 and 2 inspections.

4. The Hansol FX Hurricane Giant Flame System User Guide, copyrighted 2016 by Hansol Global Corporation, Inc., was reviewed. The NITTA Corporation “Linemate” Hose, Hose couplings and Adapters catalog, publication H-HO-12E, was reviewed.

5. The Exxonmobil Chemical Company Isoparaffinic Hydrocarbon Safety Data Sheet, for “Isopar G” Fluid, revision date November 19, 2015, was reviewed.

6. The video, https://vimeo.com/titanup/review/363435057/9e40d45b6e, from the National Football League (NFL), was reviewed.

7. National Fire Protection Association (NFPA) Standard 160-11, Standard for the Use of Flame Effects Before an Audience, was reviewed.

8. NFPA 1123-14, Code for Fireworks Display, was reviewed.

9. NFPA 1126-11, Use of Pyrotechnics Before a Proximate Audience, was reviewed.

Section V
ATTACHMENTS

A. Photographs

B. Curriculum Vitae

Section V
ATTACHMENT A

Photographs

Photographs taken during our inspection, which were not included in this report, were retained in our files and are available to you upon request.

Photograph 1
Fueled fire just after incipient stage (clip from NFL video).

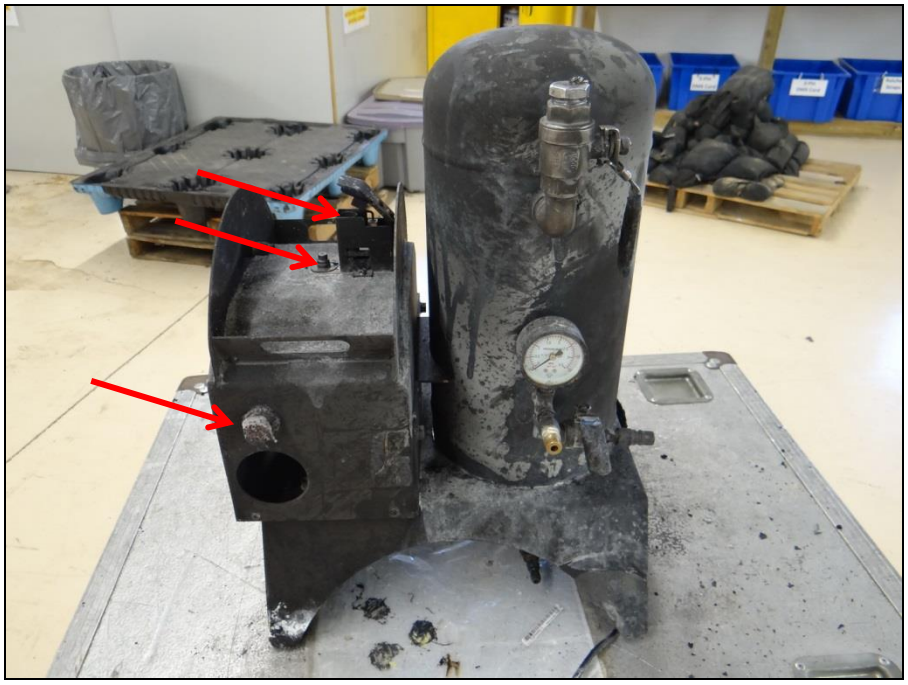
Photograph 2
Full fuel-engaged stage (photograph provided by others).

Photograph 3
Full fuel-engaged stage (photograph provided by others).

Photograph 4
Damaged field area (photograph provided by others).

Photograph 5
Flame machine.

Photograph 6
Pilot burner, fuel nozzle, and pilot manual shutoff.



Photograph 7
Failed hose.

Photograph 8
Heat-affected base.

Photograph 9
Fire-affected cart base.

Photograph 10
Signage.

Section V

ATTACHMENT B

Curriculum Vitae

RIMKUS CONSULTING GROUP, INC.
FORENSIC ENGINEERS AND CONSULTANTS

Gary L. VanderMolen, P.E.

Division Manager
Products Division

Background

Mr. VanderMolen holds a B.S. degree in Agricultural Engineering, an M.S. degree in Mechanical Engineering and an M.B.A. He is also a registered (Mechanical) Professional Engineer in Alabama, Arkansas, Georgia, Illinois, Indiana, Iowa, Kentucky, Mississippi, Missouri, New York, Ohio, and Tennessee. He has 35 years of experience in product design and manufacturing as well as program, engineering, and quality management.

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Mr. VanderMolen has broad experience in materials selection and application, engineering design and analysis, process definition, hands-on testing, development and launch, supplier development, and customer liaison. His skill areas are in safety and mission-critical control systems and structures for trucks and buses, passenger cars, utility vehicles, agricultural construction and industrial equipment, and marine vessels.

As a forensic engineer, Mr. VanderMolen is responsible for vehicle and system evaluation, failure root cause analysis, vehicle dynamics, and engineering. He has performed extensive analysis and simulation on analogous hydraulic, pneumatic, and electromechanical systems and components. Specific experience includes vehicle and system evaluation, failure root cause analysis, crash reconstruction, safety design hierarchy, as well as quality standards, codes, and regulations compliance.

2010

RIMKUS CONSULTING GROUP, INC.
FORENSIC ENGINEERS AND CONSULTANTS

Professional Engagements

- **Heavy Equipment**
  - New Product Launches – Waterloo, IA (1978-1986), Specified and integrated outsourced power steering components to match in-house system requirements, reducing system costs by 60%.

- **Commercial Vehicles and Systems**
  - New Product Launches – Elyria, OH and Lafayette, IN (1986-1998), Released new modular air dryers, hydraulic park brakes, and multiple axle and electronic controlled steering systems and for launch, broadening product offerings by 20%.
  - New Product Platform – Fort Wayne, IN (1998-2005), Led next generation truck and bus chassis and body system development and launch of a complete replacement of existing product line, increasing market share to 80%.

- **Automotive**
  - Electrically-powered Motion Actuators – Springfield, TN (2007–2012), Resolved several chronic HVAC actuator and brushless fan drive issues, improving new product quality by 35%. Instituted lean engineering.

Forensic Engagements

- **Equipment Failure and Accident Investigations**
  - Birmingham, AL (2018), Truck brakes failure
  - Tuscaloosa, AL (2017), Tractor neutral safety start switch failures
  - Montgomery, NY (2016), Truck power distribution module fires
  - Altoona, IA (2016), Tractor steering/brake controls failure
  - Chicago, IL (2014), Forklift rollover incident

- **Vehicle Accident Assessments (2013-2018)**
  - Single- and Multi-Vehicle Crashes (commercial vehicle, car, motorcycle, bicycles, and pedestrian)
  - Perception and Reaction Response Times
  - Intersection Line of Sight and Traffic Signal Analysis
  - Vehicle System Evaluation/Failure Analysis (steering and suspensions, engine and transmissions, wheels and brakes and occupant restraints)

- **Mechanical Equipment/Machinery Malfunction (2013-2018)**
  - Root cause analysis of machinery and equipment failures
  - Component and material failure evaluation
  - Destructive and nondestructive evaluation/testing

2010

RIMKUS CONSULTING GROUP, INC.
FORENSIC ENGINEERS AND CONSULTANTS

Professional Experience

- **Rimkus Consulting Group, Inc.** **2013 – Present**
  - Division Manager – Products

    Determines the cause, origin, and extent of mechanical system and product failures in the settlement of legal, civil, insurance, and corporate claims. Provides mechanical equipment and machinery malfunction analysis, product design, safety and failure analysis, and testing of products and materials. Conducts engineering investigation and analysis of mobile vehicles, and agricultural, residential, commercial, and industrial equipment and facilities. Prepares oral and written technical expert reports, opinions and testimony on causes of failure, extent of loss, and recommended remediation. Researches, inspects, tests, and gathers evidence to discern root cause, conditions, and contributory factors.

- **Johnson Electric** **2007 – 2012**
  - Director – Quality & Reliability (2010-2012)

    Responsible for quality systems, customer support, plant quality, supplier quality, and engineering labs for global powertrain cooling, HVAC actuator systems, and chassis and body motor subsystems. Led global product engineering, program and product management, and supplier development for powertrain cooling, and body and chassis actuator competence centers. Facilitated numerous Kaizen continuous improvement processes to resolve design, manufacturing, and application issues.

  - Director – Technology and Innovation North America (2007-2011)

    Led global DC motor, actuator and solenoid competence centers, engine cooling fan module development and actuator applications. Produced technical proposals for increased powertrain cooling business, tripling awarded revenue growth. Instituted improved in-house replacement for competitive motors in actuators, $3.5M annual savings.

- **Carver Yacht Group** **2006 – 2007**
  - Director – Engineering

    Responsible for all vessel systems and propulsion engineering, design, prototype and tooling build, and test, quality, supplier quality management, and product data. Developed and improved powertrain and propulsion systems for new applications.

- **Navistar** **1998 – 2005**
  - Director – Business Product Center

    Responsible for major program product development, platform upgrade programs, quality engineering, continual product and process improvement, customer support, and new technology applications to meet strategic quality, cost, and delivery objectives. Designed and released structures (cab, body, fuel, exhaust), as well as primary control systems (for chassis, powertrain, electronics, steering, and brakes).

- **TRW Automotive** **1993 - 1998**
  - Chief Engineer – Steering System
    Managed all commercial and technical aspects of advanced global steering systems design and development programs. Responsible for commercial and technical feasibilities, and design and development programs for global steering systems. Performed studies characterizing truck operator behaviors in the design and development of drowsy driver detection mechanisms. Developed and incorporated new global steering product/process technologies and strategies.

- **AlliedSignal Bendix** **1986 - 1993**
  - Staff Engineer – Brake Valves and Systems
    Technical manager for cross-functional and multi-location next generation brake and suspension chassis systems. Provided design and development support for air brake and suspension actuation and adjustment product lines. Led steering and brake controls engineering. Conducted hydraulic system performance and durability testing.

- **John Deere** **1978 - 1986**
  - Design/Analysis Engineer – Advanced Hydraulics
    Research and development for new row crop tractor steering and chassis systems. Validated and launched row crop mechanical front-wheel drive structures and hydraulics. Lab and field-tested complete row crop and four-wheel drive tractors. Performed body and chassis system harsh environment testing. Launched product design durability and reliability improvements.

Education and Certifications

- **Agricultural Engineering, B.S. (BSAE):** Iowa State University (1978)
- **Mechanical Engineering, M.S. (MSME):** Iowa State University (1985)
- **Business Administration, M.B.A.:** Cleveland State University (1989)
- **Lead Assessor and Certified Trainer:** TS16949, ISO14001
- **Six Sigma Green Belt Certification:** American Society for Quality
- **Bosch CDR Technician:** Institute of Police Technology and Management

Continuing Education

- **ACTAR Traffic Crash Reconstruction:** Institute of Police Technology and Management **(IPTM)**
- **Heavy Vehicle Crash Reconstruction:** Northwestern University Center for Public Safety (NUCPS)
- **Pedestrian Vehicle Crash Reconstruction:** (NUCPS)
- **Traffic Crash Investigation I & II:** (NUCPS)
- **Traffic Crash Reconstruction II:** (NUCPS)

Patents

- **Rollover air bag system:** US6502856B1, 2003
- **Switching valve for a hydraulic power steering system:** US6173728B1, 2001
- **Programmable vehicle stopping system and process for route learning:** US6396395B1, 2002
- **Switching valve for a hydraulic power steering system:** US6173728B1, 2001
- **Integrated active seat suspension and seat lockup device:** US6120082A, 2000
- **Integrated semi-active seat suspension and seat lockup system:** US6082715A, 2000
- **Integrated active seat suspension and seat lockup device:** US6120082A. 2000
- **Steering column:** US5678454A, 1997
- **Air dryer mechanism with flow regulated purge pressure:** US5458677A, 1995
- **Hydraulic parking brake control system:** US4923254A, 1990
- **Concentrate metering apparatus:** US4285445A, 1981

Publications

- **"Low Bandwidth Active Cab Suspension."** SAE Technical Paper 973206, 1997
- **"Resonance of a Hydraulic Pump Control System."** MSME thesis, 1978