ARC Conference 2003

Ninth Annual ARC Conference on Modeling and Simulation of Ground Vehicles

May 12-13, 2003

Daimler Chrysler
Auburn Hills, MI
University of Michigan
College of Engineering
Ann Arbor, MI

Sponsored by:

- ***Automotive Research Center***
- ***National Automotive Center (NAC)***
- ***U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)***
- ***U.S. Army Tank-Automotive and Armaments Command (TACOM)***

Registration is FREE and REQUIRED.

Please register before April 25 2003.

UNITED STATES ARMY NAC NATIONAL AUTOMOTIVE CENTER

CONFERENCE OBJECTIVES
ONLINE REGISTRATION
DAY 1 - SCHEDULE
DAY 2 - SCHEDULE
SYMPOSIA MATRIX
SYMPOSIUM ABSTRACTS
ADDITIONAL INFORMATION
MAPS

The Conference will highlight advances in ground vehicle simulation. It will present the results of ARC research to university, industry, and government stakeholders and encourage collaboration between these sectors.

Conference Program

Monday, May 12, 2003
(Located at DaimlerChrysler Technology Center, Auburn Hills)

7:30 - 8:30 am **ARRIVAL AND CONTINENTAL BREAKFAST**

Full presentations are available to ARC members on the iARC portal.

8:30 - 9:00 **WELCOME AND INTRODUCTIONS**

Dennis Assanis
Professor and ARC Director, University of Michigan
Automotive Research Center: Continues to Excel and Looks Ahead

Walter Bryzik
Chief Scientist, U.S. Army TACOM-TARDEC

Dennis Wend
Director, National Automotive Center, U.S. Army TACOM-TARDEC

9:00 - 10:30 **TOWARDS FUTURE VEHICLE CONCEPTS AND DESIGNS - MILITARY AND INDUSTRY PROSPECTIVE**

Moderator: **Dennis Assanis**
Professor and ARC Director, University of Michigan

Speakers: **Bernard Robertson**
Senior Vice President Engineering Technologies & Regulatory Affairs, DaimlerChrysler
Towards Future Vehicle Concepts and Design - Military and Industrial Perspective

Major General N. Ross Thompson III
Commander, US Army TACOM
Improving the Reliability, Maintainability, and Sustainability (RMS) of Army Systems through the Use of Probabilistic Methods

Thomas Moore
Vice President, Liberty and Technical Affairs, DaimlerChrysler
Hydrogen Source Alternatives

Roger McCarthy
Chairman, Exponent Analysis Associates, Inc.
Design optimization for reliability and robustness “You want robots in Afghanistan when??”

Question and Answer Session

10:30 - 11:00 **NETWORKING BREAK**

11:00 - 11:45 **A SIMULATION-BASED VEHICLE DESIGN STRATEGY FOR REQUIREMENTS VALIDATION**

Speakers: **Panos Y. Papalambros**
Professor, University of Michigan

VK Sharma
Director-Engineering, International Truck & Engine Corp.

Paul Skalny

Deputy Director NAC, Program Manager Future Truck Systems Initiative, U.S. Army TACOM

11:45 - 12:15pm **OVERVIEW OF NAC INITIATIVES**
Developing and Using M&S Tools

Speaker: **David Gorsich**
Research Scientist , National Automotive Center, U.S. Army TACOM-TARDEC

12:15 - 1:00 **NEW CAPABILITIES IN STRUCTURAL SIMULATION, ANALYSIS AND DESIGN: TOOLS AND APPLICATIONS**

Speakers: **Christophe Pierre**
Professor and ARC Thrust Area 3 Leader, University of Michigan

K.K. Choi
Professor, University of Iowa

1:00 - 2:15 **LUNCH** (Cafeteria)

2:15 - 3:00 **DRIVER/VEHICLE DYNAMICS INTERACTIONS**

Speakers: **Kyle Nebel**
U.S. Army TACOM

Don Chaffin
Professor and Thrust Area 2 Leader, University of Michigan
Loucas Louca
Research Scientist, University of Michigan
Kevin Rider
Research Assistant, University of Michigan
Brent Gillespie
Assistant Professor, University of Michigan

3:00 - 3:15 **NETWORKING BREAK**

3:15 - 4:00 **COMBINING DIESEL-HYBRID PROPULSION AND FUEL CELL POWER FOR ACCESSORIES**

Speakers: **Zoran Filipi**
Associate Research Scientist and ARC Assistant Director, University of Michigan

Anna Stefanopoulou
Associate Professor, University of Michigan
Loucas Louca
Research Scientist, University of Michigan
Georges Fadel
Professor, Clemson University

4:00 - 4:15 **WRAP-UP AND Q & A**
Dennis Assanis, Professor and ARC Director, University of Michigan

4:15 **ADJOURN**

Conference Program

Tuesday, May 13, 2003

(Located at the University of Michigan North Campus)

8:00 - 8:30 **REGISTRATION AND CONTINENTAL BREAKFAST**

8:30 - 9:00 **WELCOME AND INTRODUCTION** (Auditorium)

Dennis Assanis, Professor and ARC Director, University of Michigan

David Gorsich, Chief Scientist, National Automotive Center

Walter Bryzik, Chief Scientist, U.S. Army TACOM-TARDEC

9:00 - 4:50 **PARALLEL SYMPOSIA I-IV**
The balance of the day's activities was divided into **four** Parallel Symposia. They will run concurrent sessions concentrating on specific technical issues. A session matrix plan and abstracts of the technical presentations are included to allow attendees to select from the various topics presented to match their technical interests.

Due to the large number of sessions and ever-increasing file sizes of the presentations, we are unable to archive the symposia content on the web site.
Kindly contact the presenters of the sessions in which you have interest.
ARC Members may visit the iARC portal Conference Archives.

Presenters/Contributors are listed in the Symposim Abstracts page and the Day 2 Abstracts handout in your Conference folder.

	Symposium I
	1A Robotics & Autonomous Vehicles
9:00 - 9:25	1A-1 Decentralized Control for a Team of Physically Cooperating Robots
9:25 - 9:50	1A-2 Lightweight Robotic Mobility Using ADAMS/Car and MATLAB
9:50 - 10:15	1A-3 Mobility Analysis of Small, Lightweight Robotic Vehicles
10:15 - 10:40	1A-4 Sweeping Laser Rangefinders in Mobile Robot Obstacle Negotiation and Map-Building Applications
10:40 - 11:00	**BREAK**
	1B Design and Control of Vehicle Systems
11:00 - 11:25	1B-1 LTI Design Optimization for Ease of Observation and Regulation, with Application to Combined Passive/Active Car Suspension
11:25 - 11:50	1B-2 Matrices as Modeling Tools in Scenario-oriented Multicriteria Vehicle Design
11:50 - 12:15	1B-3 Data-based Evaluation of Collision Warning and Avoidance Algorithms
12:15 - 1:15	**LUNCH** (FXB Building)
	1C Modeling and Control of Vehicle Systems
1:15 - 1:40	1C-1 A Stochastic Approach to Control Strategy Development for Hybrid Vehicles
1:40 - 2:05	1C-2 Modeling, Analysis, and Control of Medium Duty Vehicle Steer-by-Wire Systems
2:05 - 2:30	1C-3 Model Partitioning for Improved Simulation-Based Design
2:30 - 2:55	1C-4 Continuous and Discrete Models for Dynamic Response of Belt CVTs
2:55 - 3:20	**BREAK**
	1D Imaging & Visualization
3:20 - 3:45	1D-1 Multi-Modal 3D Object Reconstruction for Inspection and Reverse Engineering
3:45 - 4:10	1D-2 Fast Digitization of Real World Environments for Evaluation of Driver Behaviors

4:10 - 4:35	1D-3 Multi-Perspective Mosaics from Video Imagery for Driver Simulation and Vehicle Inspection
4:35 - 5:00	1D-4 Superquadrics-based 3D object Representation of Automotive Parts Utilizing Part Decomposition
	Symposium II
	2A Human Centered Design
9:00 - 9:25	2A-1 Modeling Reach Difficulty for Truck Drivers
9:25 - 9:50	2A-2 Seated Reach-Balance Modeling
9:50 - 10:15	2A-3 Shoulder Biomechanical Modeling of Reaches
10:15 - 10:40	2A-4 Vibration Feedthrough Cancellation for Joystick Controlled Vehicles
10:40 - 11:00	**BREAK**
	2B Recent Progress in NVH Analysis
11:00 - 11:25	2B-1 Energy Boundary Element and Hybrid Finite Element Developments
11:25 - 11:50	2B-2 Reduction Techniques for Component-Mode-Based Vibration Analysis of Vehicle Structures
11:50 - 12:15	2B-3 Identification Technique of Global Modeshapes from A Few Nodal Eigenvectors
12:15 - 1:15	**LUNCH** (FXB Building)
	2C Structural Design Sensitivity and Uncertainty Analysis
1:15 - 1:40	2C-1 Statistical Approximations of Power Flow for a Vehicle Structure with Uncertainties
1:40 - 2:05	2C-2 Design Sensitivity Analysis and Optimization of High Frequency Structural-Acoustic Problems Using Energy Finite Element Method
2:05 - 2:30	2C-3 Reliability-Based Design Optimization of Structural Durability under Manufacturing Tolerances
2:30 - 2:55	2C-4 Efficient Evaluation Approaches for Probabilistic Constraints in Reliability-Based Design Optimization
2:55 - 3:20	**BREAK**
	2D Vehicle-Terrain Interaction Modeling & Simulation
3:20 - 3:45	2D-1 Interaction between a pneumatic tire and snow
3:45 - 4:10	2D-2 Simulation of vehicle dynamics with tire/ground interface using Simulink
4:10 - 4:35	2D-3 High Fidelity Vehicle-Terrain Interaction Modeling and Simulation
4:35 - 5:00	2D-4 Tracked Vehicle Dynamic Simulation: Robot Vehicle and Real-Time Simulation
	Symposium III
	3A Fuel Cell Power
9:00 - 9:25	3A-1 Instrumentation Acquisition and Development of a Fuel Cell Control Laboratory
9:25 - 9:50	3A-2 Control of Fuel Cell Breathing: Addressing the Oxygen Starvation Problem
9:50 - 10:15	3A-3 Assessing Model Range of Validity: A Fuel Cell Case Study
10:15 - 10:40	3A-4 Thermal Modeling of PEMFC
10:40 - 11:00	**BREAK**
	3B Hybrids & Powertrain Electrification
11:00 - 11:25	3B-1 Modeling of Electric Acessories and Fuel Cell APU for the FMTV Truck
11:25 - 11:50	3B-2 Reduction of Parasitic Losses of the FMTV Truck through Electrification
11:50 - 12:15	3B-3 Field Investigation of Military Hybrid Vehicle Performance
12:15 - 1:15	**LUNCH** (FXB Building)
	3C Diesel Spray, Combustion and Heat Transfer
1:15 - 1:40	3C-1 A New Model for Combustion and Emissions in High Speed Diesel Engines
1:40 - 2:05	3C-2 Simulation of Fuel Injection Dynamics and High-speed Fuel Spray
2:05 - 2:30	3C-3 Development of Diesel Engine Emissions and Performance (DEEP) Model for Engine-in-vehicle Simulation
2:30 - 2:55	3C-4 Development and Validation of Unsteady Convective Heat Transfer Correlation
2:55 - 3:20	**BREAK**
	3D Modeling Engine Processes and Systems
3:20 - 3:45	3D-1 High Power Density Diesel Cycle Simulation
3:45 - 4:10	3D-2 Variable Geometry Turbocharging for Enhanced Performance and Transient Response - a Retrofit Study

4:10 - 4:35	3D-3 Development of an EDC-based combustion model for diesel combustion
4:35 - 5:00	3D-4 Two-Dimensional Effects in the lubrication of the cam tappet contact
	Symposium IV
	4A Multilevel Systems Optimization
9:00 - 9:25	4A-1 Using Discrete-Event Simulation Tools to Specify and Implement Coordination Strategies in Multilevel Systems Optimization
9:25 - 9:50	4A-2 Multilevel Systems Optimization under Uncertainty
9:50 - 10:15	4A-3 Lagrangian Coordination for Large-Scale Systems Revisited
10:15 - 10:40	4A-4 The Step after Analytical Target Cascading: Analytical Target Setting
10:40 - 11:00	**BREAK**
	4B Simulation Environments
11:00 - 11:25	4B-1 A Gluing Algorithm for Distributed Simulation Of Multibody Systems
11:25 - 11:50	4B-2 Vehicle Modeling and Simulation Environment for Off-Road Applications
11:50 - 12:15	4B-3 Solving the Acceleration Equations Using a Projection Method
12:15 - 1:15	**LUNCH** (FXB Building)
	4C CAE Methodologies, Thermal Signature
1:15 - 1:40	4C-1 Signature Analysis of Vehicles and Automotive Components Using Thermal Imaging and 3D Information
1:40 - 2:05	4C-2 Virtual Thermal Management Design and Evaluation
2:05 - 2:30	4C-3 Shell Extraction of 3D CAD models for Packaging applications
2:30 - 2:55	4C-4 Multi-Objective Configuration Optimization with Vehicle Dynamics Applied to a Mid-Size Truck
2:55 - 3:20	**BREAK**
	4D Automotive Product Development
3:20 - 3:45	4D-1 An Enterprise Decision Model for Optimal Vehicle Design and Technology Valuation
3:45 - 4:10	4D-2 Efficient Product Portfolio Reduction
4:10 - 4:35	4D-3 A Study of Emission Policy Effects on Optimal Vehicle Design Decisions
4:35 - 5:00	4D-4 Multi-Scenario Multi-Criteria Optimization in Engineering Design
5:00	**ADJOURN**

Exhibits and Tour

DaimlerChrysler vehicles will be on display at DCX the first day. The second day will feature the Dodge Ram COMBATT vehicle. In addition a tour of the UM Walter E. Lay Automotive Research Laboratory and the new Fuel Cell Control Laboratory will be given to interested parties. Individuals interested in the tour will need to sign up at the registration desk by noon on the second day.

Time	Symposium I		Symposium II		Symposium III		Symposium IV	
9:00 – 9:25	**Robotics & Autonomous Vehicles**	Decentralized Control for a Team of Physically Cooperating Robots	**Human Centered Design**	Modeling Reach Difficulty for Truck Drivers	**Fuel Cell Power**	Instrumentation Acquisition and Development of a Fuel Cell Control Laboratory	**Multilevel Systems Optimization**	Using Discrete-Event Simulation Tools to Specify and Implement Coordination Strategies in Multilevel Systems Optimization
9:25 – 9:50		Lightweight Robotic Mobility Using ADAMS/Car and MATLAB		Seated Reach-Balance Modeling		Control of Fuel Cell Breathing: Addressing the Oxygen Starvation Problem		Multilevel Systems Optimization under Uncertainty
9:50 – 10:15		Mobility Analysis of Small, Lightweight Robotic Vehicles		Shoulder Biomechanical Modeling of Reaches		Assessing Model Range of Validity: A Fuel Cell Case Study		Lagrangian Coordination for Large-Scale Systems Revisited
10:15 – 10:40		Sweeping Laser Rangefinders in Mobile Robot Obstacle Negotiation and Map-Building Applications		Vibration Feedthrough Cancellation for Joystick Controlled Vehicles		Thermal Modeling of PEMFC		The Step after Analytical Target Cascading: Analytical Target Setting
10:40 – 11:00	**Break**							
11:00 – 11:25	**Design and Control of Vehicle Systems**	LTI Design Optimization for Ease of Observation and Regulation, with Application to Combined Passive/Active Car Suspension	**Recent Progress in NVH Analysis**	Energy Boundary Element and Hybrid Finite Element Developments	**Hybrids & Powertrain Electrification**	Modeling of Electric Acessories and Fuel Cell APU for the FMTV Truck	**Simulation Environments**	A Gluing Algorithm for Distributed Simulation Of Multibody Systems
11:25 – 11:50		Matrices as Modeling Tools in Scenario-oriented Multicriteria Vehicle Design		Reduction Techniques for Component-Mode-Based Vibration Analysis of Vehicle Structures		Reduction of Parasitic Losses of the FMTV Truck through Electrification		Vehicle Modeling and Simulation Environment for Off-Road Applications
11:50 – 12:15		Data-based Evaluation of Collision Warning and Avoidance Algorithms		Identification Technique of Global Mode Shapes from A Few Nodal Eigenvectors		Field Investigation of Military Hybrid Vehicle Performance		Solving the Acceleration Equations Using a Projection Method
12:15 – 1:15	**Lunch**							
1:15 – 1:40	**Modeling and Control of Vehicle Systems**	A Stochastic Approach to Control Strategy Development for Hybrid Vehicles	**Structural Design Sensitivity and Uncertainty Analysis**	Statistical Approximations of Power Flow for a Vehicle Structure with Uncertainties	**Diesel Spray, Combustion and Heat Transfer**	A New Model for Combustion and Emissions in High Speed Diesel Engines	**CAE Methodologies, Thermal Signature**	Signature Analysis of Vehicles and Automotive Components Using Thermal Imaging and 3D Information
1:40 – 2:05		Modeling, Analysis, and Control of Medium Duty Vehicle Steer-by-Wire Systems		Design Sensitivity Analysis and Optimization of High Frequency Structural-Acoustic Problems Using Energy Finite Element Method		Simulation of Fuel Injection Dynamics and High-speed Fuel Spray		Virtual Thermal Management Design and Evaluation
2:05 – 2:30		Model Partitioning for Improved Simulation-Based Design		Reliability-Based Design Optimization of Structural Durability under Manufacturing Tolerances		Development of Diesel Engine Emissions and Performance (DEEP) Model for Engine-in-vehicle Simulation		Shell Extraction of 3D CAD models for Packaging applications

2:30 – 2:55		Continuous and Discrete Models for Dynamic Response of Belt CVTs		Efficient Evaluation Approaches for Probabilistic Constraints in Reliability-Based Design Optimization		Development and Validation of Unsteady Convective Heat Transfer Correlation		Multi-Objective Configuration Optimization with Vehicle Dynamics Applied to a Mid-Size Truck
2:55 – 3:20	**Break**							
3:20 – 3:45	**Imaging & Visualization**	Multi-Modal 3D Object Reconstruction for Inspection and Reverse Engineering	**Vehicle-Terrain Interaction Modeling & Simulation**	Interaction between a pneumatic tire and snow	**Modeling Engine Processes and Systems**	High Power Density Diesel Cycle Simulation	**Automotive Product Development**	An Enterprise Decision Model for Optimal Vehicle Design and Technology Valuation
3:45 – 4:10		Fast Digitization of Real World Environments for Evaluation of Driver Behaviors		Simulation of vehicle dynamics with tire/ground interface using Simulink		Variable Geometry Turbocharging for Enhanced Performance and Transient Response - a Retrofit Study		Efficient Product Portfolio Reduction
4:10 – 4:35		Multi-Perspective Mosaics from Video Imagery for Driver Simulation and Vehicle Inspection		High Fidelity Vehicle-Terrain Interaction Modeling and Simulation		Development of an EDC-based Combustion Model for Diesel Combustion		A Study of Emission Policy Effects on Optimal Vehicle Design Decisions
4:35 – 5:00		Superquadrics-based 3D object Representation of Automotive Parts Utilizing Part Decomposition		Tracked Vehicle Dynamic Simulation: Robot Vehicle and Real-Time Simulation		Two-Dimensional Effects in the Lubrication of the Cam Tappet Contact		Multi-Scenario Multi-Criteria Optimization in Engineering Design

Conference Program

Day 2

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Symposium I

1A Robotics & Autonomous Vehicles

1A-1 **Decentralized Control for a Team of Physically Cooperating Robots**
Ashish Deshpande

A team of small, low cost robots instead of one big, complex robot is useful in operations such as search and rescue, urban exploration etc. However, the performance of such a team is limited due to restricted mobility of the team members. We propose to overcome the mobility restrictions by physical cooperation among the team members. We carry out a feasibility analysis of a particular behavior of two robots cooperating to cross a gap. We simulate the dynamic equations describing the motion which leads the relaxation the requirements derived from the static analysis. A decentralized control architecture is designed which avoids continuous communication between the robots thus rendering the cooperation to be simple and low cost.

1A-2 **Lightweight Robotic Mobility Using ADAMS/Car and MATLAB**
Peter Adamczyk

The U.S. Army is seeking to develop autonomous off-road mobile robots to perform tasks in the field such as supply delivery and reconnaissance in dangerous territory. A key problem to be solved with these robots is off-road mobility, to ensure that the robots can accomplish their tasks without loss or damage. We have developed a computer model of one such concept robot, the small-scale "T1" omnidirectional vehicle (ODV), to study the effects of different control strategies on the robot's mobility in off-road settings. We built the dynamic model in ADAMS/Car and the control system in MATLAB/Simulink. This presentation showcases simulation results from the T1 modeling project, including the scalability advantages of the template-based method used to construct the ADAMS model. It discusses the strengths and weaknesses of ADAMS/Car software in such an application, and describes the benefits and challenges of the approach as a whole. The presentation also addresses effective linking of ADAMS/Car and MATLAB for complete control system development. Finally, current and future work to improve and utilize the simulations are described.

1A-3 **Mobility Analysis of Small, Lightweight Robotic Vehicles**
Brooke Haueisen

Currently, the Army is developing a smaller, leaner fighting force as part of the Future Combat Systems initiative. Therefore, there is an emphasis on small, lightweight vehicle systems (less than 2000 lbs), including small robotic systems. When the Army is presented with a new vehicle concept, the NATO Reference Mobility Model (NRMM) is utilized to determine the 'go / no go' capability. Another fundamental method for predicting large vehicles' behavior on varied terrain is to use Bekker's equations for vehicle soil interaction. These equations form a phenomenological model that describes a vehicle's performance using inputs defining the vehicle's weight, wheel or tracked design, and the necessary soil parameters. Although Bekker derived semi-empirical formulations and the NRMM used entirely empirical relations for the terrain interaction of large, heavyweight vehicles, it is unclear whether these formulations scale to smaller, lightweight systems. There is additional model uncertainty when looking at other forms of exotic mobility that do not utilize a traditional wheel or track configuration. This study presents a state-of-the-art analysis on the metrics that define small vehicle mobility and possible approaches to addressing exotic robot mobility classification.

1A-4 Sweeping Laser Rangefinders in Mobile Robot Obstacle Negotiation and Map-Building Applications

Johann Borenstein, Cang Ye

All mobile robots require obstacle negotiation capabilities in order to move around safely. The foremost problem in the implementation of this capability is that current sensor technology is very expensive,typically requiring 3-DOF laser rangefinder and fast computer vision systems costing over $100K. The project presented here aims at developing a system capable of producing accurate elevation maps for obstacle negotiation, but using only a much more affordable 2-DOF laser rangefinder. One essential requirement for this cost-effective approach is that the rangefinder's momentary position and orientation (collectively called "pose") be known at any time and with good accuracy. The focal points of our project are thus: The development of elevation maps from 2-DOF laser rangefinders during motion; The integration of a pose estimation system with the laser rangefinder and the isolation of this system from motion-induced disturbances.

1B Design and Control of Vehicle Systems

1B-1 LTI Design Optimization for Ease of Observation and Regulation, with Application to Combined Passive/Active Car Suspension

Hosam Fathy

The problems of optimizing a vehicle system's design (plant), regulation and estimation are coupled: solving them sequentially does not guarantee system optimality. Numeric, experimental, and set theoretic demonstrations of this coupling, and strategies proposed in the literature to mitigate it, are reviewed. A comparison of the necessary conditions for plant (KKT), regulation (Pontryagin), estimation (Wiener-Hopf), and combined optimality furnishes quantitative measures of this coupling and a classification of scenarios where it ceases to exist. Nested optimization strategies that guarantee system optimality are proposed and applied to combined plant/LQR and combined plant/LQG control optimization for a combined passive/active car suspension. The resulting optimal suspension systems outperform their passive, active, and sequentially optimized passive/active counterparts in both the time and frequency domains. Comparing the optimal suspension systems for the LQR and LQG cases reveals a potential connection between a system's robustness and the coupling between the optimization of its plant and control.

1B-2 Matrices as Modeling Tools in Scenario-oriented Multicriteria Vehicle Design

Brian J. Hunt, Margaret M. Wiecek

The choice of a preferred design for a vehicle design problem modeled within the framework of multiscenario multicriteria optimization is a challenging task. We propose to support designers with a simple tool generalizing the classical multicriteria optimization based on Pareto optimality. While the classical approach can be viewed as using an identity matrix, we introduce a class of matrices modeling scenario-oriented information about the criteria and allowing for the inclusion of this information in the optimization process. The possibilities include scaling and/or weighting of criteria, relative importance of criteria, tradeoff allowances and constraints on criteria, reduction or enlargement of the Pareto set. We demonstrate these issues in the context of a vehicle design problem.

1B-3 **Data-based Evaluation of Collision Warning and Avoidance Algorithms**
Kangwon Lee

Manufacturers have been working on the CW/CA systems targeting major type of traffic accidents but their logics have not been compared with large real driving data yet. We extracted two subsets of the data: "dangerous" and "safe" driving situations from ICC FOT database provided by UMTRI. Using these subsets, we evaluated three of the existing CW/CA algorithms: Honda, Mazda and the Johns Hopkins University (APL), which is later used as part of the CAMP algorithm. None of these algorithms work satisfactorily yet.

1C Modeling and Control of Vehicle Systems

1C-1 **A Stochastic Approach to Control Strategy Development for Hybrid Vehicles**
Chan-Chiao (Joe) Lin and Huei Peng

The control strategy for hybrid vehicles plays a crucial role in managing and coordinating overall vehicle systems in order to maximize the potential for improving the fuel economy and reducing the exhaust emissions. However, most of the control strategy developments rely on intuition and a heuristic way to identify the controller. The result of the control strategy is often inherently cycle-beating and is lack of an optimal battery management (charge-sustaining) strategy. In this study, the problem is tackled from a stochastic point of view. An infinite-horizon stochastic dynamic optimization problem is formulated to simultaneously minimize the fuel consumption and emissions. The power demand from the driver is modeled as a random process by using Markov chain. The estimated Markov model can be used to determine the probability distribution of future demands or generate samples of synthetic demands, which creates diversified random driving scenarios. The optimal control strategy is then solved by using Stochastic Dynamic Programming (SDP) technique. The control law is in the form of stationary full-state feedback, which is directly implementable. More importantly, an optimal charge-sustaining strategy is imbedded in the control law from this SDP approach. Simulation results over standard driving cycles and random driving cycles will be presented to demonstrate the effectiveness of the proposed control strategy.

1C-2 **Modeling, Analysis, and Control of Medium Duty Vehicle Steer-by-Wire Systems**
Pradeep Setlur, Santosh Ancha, Jian Chen, Dr. John Wagner, Dr. Darren Dawson

Hybrid vehicles have motivated steer-by-wire technology due to restrictions on power source availability. In addition to being more efficient, flexible and environment-friendly, these steering systems also provide the opportunity for semi-autonomous vehicle operation. Additional improvements can be achieved with marginal cost increase by incorporating four-wheel steering, which includes an additional steering mechanism to electronically control the rear wheel steering. This results in better lateral vehicle performance, reduced transient time for steering maneuvers, and avoidance of undesirable vehicle motions. Counter-phase rear steering results in greater maneuverability at low speeds while same-phase rear steering achieves improved stability at high speeds. The creation of a simulation tool to support the evaluation of four-wheel steering systems in medium-duty vehicles will provide improved design decision-making and steering, chassis, and driver interactions for various vehicle and steering system design configurations. In this project, mathematical models will be developed for steer-by-wire steering systems (front, front/rear and distributed) with an accompanying nonlinear controller to regulate the steering system. Simulation results, using VESIM, and representative numerical results for the control laws will be presented and discussed. The dynamic models for the four wheel steering assembly, servo-motors, platform dynamics, tire/road interface, and wheel dynamics will be validated and integrated to provide an engineering design tool.

1C-3 **Model Partitioning for Improved Simulation-Based Design**
Geoff Rideout

In mature research areas, simulation-based design can often be simplified through one-way coupling assumptions, valid for a given environment and system configuration. For example, a vehicle mobility model may assume that longitudinal acceleration over smooth terrain is not affected by vehicle pitch and bounce. A point mass model without suspensions or rotational degrees of freedom may suffice. As the terrain severity increases and vehicle parameters change, however, this assumption may become invalid. Any a priori model reduction assumptions should be tested initially and throughout the design process. An algorithm is demonstrated that systematically searches a model and identifies sets of dynamic elements, or partitions, between which one-way power flow occurs. The method quantitatively discovers, validates, or tracks the degradation of, one-way coupling assumptions as the system or environment change. The model partitioning algorithm also increases the scope and robustness of existing model simplification techniques. Further, optimal design of a large system is expected to be more efficient if individual partitions - reduced-order submodels - can be identified and designed independently. Vehicle dynamic applications are discussed and demonstrated.

1C-4 **Continuous and Discrete Models for Dynamic Response of Belt CVTs**
Nilabh Srivastava, Miao Yi, Imtiaz-Ul-Haque

Continuously variable transmission (CVT) is an emerging automotive technology that offers a continuum of gear ratios between two extremes. CVTs have presented the manufacturers and the engineers with alternatives much more advantageous than the conventional manual and automatic transmissions. The present research focuses on the development of simulation models that capture the essential dynamics of belt and link type CVTs. Two models were developed to accomplish this objective: a metal pushing-belt model (continuous model) and a chain link model (discrete model). The friction is modeled according to continuous Coulomb friction approximation theory. Studies were conducted to observe the influence of inertial and loading conditions on the slip behavior and torque transmitting ability of the CVT. The computational scheme, the mathematical models and the results corresponding to different loading scenarios are discussed.

1D Imaging & Visualization

1D-1 **Multi-Modal 3D Object Reconstruction for Inspection and Reverse Engineering**
Faysal Boughorbal, Andreas Koschan, and Mongi Abidi

The goal of this research is to develop efficient techniques for the modeling of real world scenes and objects from multiple range maps and color images. To achieve this objective we had to address the important problem of sensor registration and fusion. In this work we designed a new Shape Correlation method for the merging of 3D data sets. The method operates at the point level and defines a global metric, which is maximized for the correct pose parameters. By employing robust feature inference tools, the new technique addressed several outstanding problems of 3D registration, such as the sensitivity to partially overlapping datasets, noise, and sparse data. The Shape Correlation algorithm has several additional potential applications in the areas of 2D image alignment, object recognition, and non-rigid registration. The second main contribution of this research is the design of a system that fuses range maps and multiple color images using warping approaches. The system performs fusion at the intensity level, where texture maps are computed from images and applied to 3D models reconstructed from range data. Furthermore, sparse shape information extracted from the images is combined with the dense range data using geometric warping transformations. The pipeline was effectively employed in applications such as reverse engineering and urban scenes modeling.

1D-2 **Fast Digitization of Real World Environments for Evaluation of Driver Behaviors**
Brad Grinstead, Michael Roy, Andreas Koschan, Mongi Abidi

The objective of this research is to reconstruct 3D environments from range and color images that can be used for the evaluation of test driver behavior. To digitize these large-scale environments in an efficient manner, a system is being developed to acquire the 3D geometry and color images from a vehicle moving past the scene at normal driving speeds. Accurate geometry is captured by a high end laser range scanner and is textured using high-resolution digital images. Pose estimation for each data sample is performed via data fusion of several sensors, including GPS and INS. Due to the large amounts of data inherent in such a scanning process (millions of data points), an adaptive surfacing algorithm is used to retain the geometry while reducing the amount of stored data and increasing the efficiency of the visualization. The reconstructed models are accurate in color and geometry and can thus be used to populate a simulator environment to a higher degree of realism than has been previously possible. This allows for the evaluation of driver performance in a realistic simulator environment. Experimental results are presented for real range and color data of large-scale outdoor scenes.

1D-3 **Multi-Perspective Mosaics from Video Imagery for Driver Simulation and Vehicle Inspection**
Jin-Choon Ng, Andreas Koschan, Mongi Abidi

The objective of this research is to investigate techniques for generating large, high-resolution mosaics from video taken from road scenes and from the underside of vehicles. The challenge lies in mosaicking scenes exhibiting significant motion parallax, large homogenous areas where motion cannot be detected, and multiple foreground objects occluding the objects of interest in a scene. This presentation will outline the efforts made to deal with these problems using basic motion analysis techniques without the use of external measurements of camera velocity, as well as the results obtained using video sequences of real-world environments.

1D-4 **Superquadrics-based 3D object Representation of Automotive Parts Utilizing Part Decomposition**
Yan Zhang, Andreas Koschan, Mongi Abidi

Object representation denotes representing three-dimensional (3D) real-world objects with known graphic or mathematic primitives recognizable to computers. This research has numerous applications for object-related tasks in areas including computer vision, computer graphics, reverse engineering, etc. The superquadric, as a volumetric and parametric model, is able to represent a large family of solid shapes compactly by an equation with a few varying parameters. Superquadric representation of multi-part objects has been an unsolved problem due to the complex geometry of objects. This presentation adresses this problem by incorporating human perception-based part decomposition. In our system, 3D models for automotive parts are first reconstructed from multi-view range scans. Next, these 3D models are represented by superquadrics. With our approach, a 3D model consisting of thousands of vertices and triangle meshes can be represented by several superquadrics, each of which contains only 11 parameters. The large data compression ratio achieved by superquadrics makes tasks such as scene visualization, data transmission, etc. able to be performed in real time.

Symposium II

2A Human Centered Design

2A-1 **Modeling Reach Difficulty for Truck Drivers**
Matt Reed

A new approach has been developed for assessing seated reaches in vehicle cabs. An innovative laboratory technique is used to adaptively sample maximum reach capability and submaximal reach difficulty. Right-handed, push-button reaches were studied for 60 men and women, including 40 with truck or bus driving experience. The data were analyzed to create an integrated model of maximum reach capability and submaximal reach difficulty for each participant. An analysis of the model parameters showed that the overall shape of the function was similar across participants and that a generic function scaled by anthropometry could produce predictions with good precision. When convolved with a model of driver-selected seat position, the reach-difficulty model can be used to create predictions of reach capability and difficulty for diverse populations of truck and bus drivers.

2A-2 **Seated Reach-Balance Modeling**
Matthew Parkinson

Seated reaches are limited by one or a combination of three task requirements: strength, range of motion, or balance maintenance. While balance has been studied in situations where operators are standing, little has been done for the seated case (e.g. when a subject is within a vehicle). ARC-sponsored work in this area has resulted in a population model of balance-maintenance capabilities. This model is readily incorporated into ergonomic design tools, allowing designers to examine the balance requirements of designs while still in the early stages of the process.

2A-3 **Shoulder Biomechanical Modeling of Reaches**
Clark Dickerson

A biomechanical model of the shoulder is being developed for dynamic reaching task analysis. The model has seen significant improvements and upgrades in the last year. An improved visualization of shoulder motions and their effects on muscle force direction has been created, as well as realistic muscle wrapping around anatomical obstructions. The framework for a muscle force prediction optimization-based model has also been constructed and is in the implementation phase. In addition, significant correlations have been identified between shoulder torque loading and the level of effort perceived by a subject, allowing prediction of perceived effort for a reaching task from empirical data. Completion of the muscle force prediction portion of the model is expected to improve comfort and effort prediction ability associated with a task, which will result in more informed vehicle interior design choices.

2A-4 **Vibration Feedthrough Cancellation for Joystick Controlled Vehicles**
Szabolcs Sövényi, R. Brent Gillespie

Vibration feedthrough refers to the effects of ride motion acting through the driver's body to produce unintentional command signals on the manual controls of a vehicle. Joystick-controlled vehicles and joystick-controlled auxiliary devices driven onboard moving vehicles are especially susceptible to vibration feedthrough. We propose to cancel the effects of vibration feedthrough using control signals derived from on-board accelerometers and applied through motors integrated into the joystick. The effectiveness of our approach has been demonstrated for both the vehicle control and auxiliary device control cases in limited human subject testing. The deterioration of tracking performance of a human subject was first demonstrated in targeting tasks onboard a moving Ride Motion Simulator (RMS). Then tracking performance under the same ride motion conditions improved with the vibration feedthrough cancellation controller in place. Also, tracking performance in the vehicle control (driving) task was shown to degrade due to the presence of a resonance in the coupled vehicle/driver biomechanics system and this resonance was suppressed with the cancellation controller in place.

2B Recent Progress in NVH Analysis

2B-1 **Energy Boundary Element and Hybrid Finite Element Developments**
Nick Vlahopoulos*, Sang-Bum Hong

The Energy Boundary Element Analysis (EBEA) constitutes a new formulation for computing high frequency acoustic radiation. The theoretical background and validation of the EBEA with test data will be presented. The EBEA constitutes a significant improvement over the traditional Statistical Energy Analysis (SEA) for high frequency exterior acoustic analysis. The SEA approximates an exterior domain as an assembly of several enclosed cavities and requires the definition of artificial damping and non-physical coupling loss factors between subsystems. The new EBEA formulation eliminates all these approximations. The hybrid FEA development effort is continued for coupling conventional FEA with EFEA. Analyses are performed using a conventional dense FEA model and a hybrid FEA approach for an assembly of plates spot-welded on a frame structure. Results between the two methods are compared successfully in the mid-frequency range.

2B-2 **Reduction Techniques for Component-Mode-Based Vibration Analysis of Vehicle Structures**
Geng Zhang*, Matthew P. Castanier, and Christophe Pierre

When the finite element model of a complex structure is partitioned into many substructures in order to enable component mode synthesis (CMS), a large number of degrees of freedom (DOF) may be associated with the interface between components. In such cases, the constraint-mode-based transformations at the substructure analysis stage could be computationally costly, and the reduced order model (ROM) obtained from the Craig-Bampton method could be still cumbersome because of the dominant interface DOF. A more efficient CMS procedure and a more compact ROM can be obtained by a further reduction of the interface DOF. Several existing interface reduction methods are reviewed and compared. A new method is proposed to obtain interface modes using simplified interface mass and stiffness matrices. This new method enables an efficient solution of interface modes. It also improves the efficiency of the corresponding CMS procedure through computational savings for the constraint-mode-based transformations at the substructure analysis stage. Numerical results of an application to a vehicle model are provided to demonstrate the performance of the proposed method.

2B-3 **Identification Technique of Global Mode Shapes from A Few Nodal Eigenvectors**
Y. Hahn and N. Kikuchi

An approach to identify several lowest eigenvalues of very-large-scale models, which was proposed at the 2002 ARC Conference, was found to be not well suited for identifying mode shapes. Because of the large model size, it is difficult to write all nodal eigenvectors from the simulation. Therefore, a new method is proposed to identify each mode from a few nodal results. The proposed method consists of two parts, Delaunay tessellation and barycentric coordinates. Using this approach, global mode shapes can be identified successfully. Several examples are presented that show good performance of the proposed method.

2C Structural Design Sensitivity and Uncertainty Analysis

2C-1 **Statistical Approximations of Power Flow for a Vehicle Structure with Uncertainties**
Soo-Yeol Lee*, Matthew P. Castanier, and Christophe Pierre

An efficient approach is presented for probabilistic power flow analysis of complex structures with parameter uncertainties. A component-based technique is used to generate reduced order models of low- to mid-frequency vibration and power flow. The reduced order model (ROM) is built from component mode synthesis of finite element models, followed by a secondary modal analysis to reduce the number of degrees of freedom associated with the component interfaces. This formulation allows for efficient and accurate prediction of vibration transmission in complex structural systems. Then, this methodology is extended to the study of statistical approximations of the power flow for a structure with parameter uncertainties. Two techniques are employed for probabilistic power flow analysis: (1) a locally linear interpolation (LLI) method for low-dimensional random variable domains, and (2) an advanced mean value (AMV) method for multi-dimensional random variable domains. In addition, an extended version of the AMV method is presented for uncertainties characterized by a uniform distribution. These statistical approximations of power flow are first demonstrated for a simple example system, an L-shaped plate. They are then examined in more detail for an important engineering application, a ground vehicle model.

2C-2 **Design Sensitivity Analysis and Optimization of High Frequency Structural-Acoustic Problems Using Energy Finite Element Method**

K.K. Choi and J. Dong*, University of Iowa, N. Vlahopoulos, A. Wang, and W. Zhang, University of Michigan

A design sensitivity analysis of high frequency structural-acoustic problem is formulated and presented. The Energy Finite Element Method (EFEM) is used to predict the structural-acoustic responses in high frequency range, where the coupling between the structural and acoustic domains are modeled by using structural-structural and structural-acoustic power transfer coefficients. The continuum design sensitivity formulation is derived from the governing equation of EFEM and the discrete method is applied for the variation of the structural-structural and structural-acoustic coupling matrix. The direct differentiation and adjoint variable method are both developed for sensitivity analysis, where the difficulty of the adjoint variable method is overcome by solving the conjugate of the equation. Parametric design variables such as the panel thickness and material hysteresis damping are considered for sensitivity analysis, and the numerical sensitivity results show excellent agreement comparing with the finite difference results. A complex vehicle structure is studied for the purpose of design optimization. The sequential quadratic programming algorithm is applied in design optimization process, where the design objective is defined to minimize the vehicle weight with design constraints are defined for the interior noise level at the driver's ear position at a high frequency range from 800 to 1600 Hz. Two different optimization examples are studied, for which the body-in-white (BIW) weight is minimized and the noise level is reduced.

2C-3 **Reliability-Based Design Optimization of Structural Durability under Manufacturing Tolerances**

K.K. Choi* and B. D. Youn, University of Iowa

Transient dynamic loadings applied during the service life of a mechanical system leads to structural fatigue that is the primary design concern in terms of durability. Uncertainties in the dimensions and material properties of a structural component due to manufacturing tolerances cause significant indeterministic nature of fatigue life of a structural component. A probabilistic design approach for structural durability that takes various uncertainties into account provides a reliable design with a required fatigue life. The objective of this presentation is to develop and apply the RBDO process for structural durability to obtain a reliable and durable design under manufacturing constraints. Since uncertainty propagation to structural fatigue under transient dynamic loading is numerically complicated and computationally expensive, it is challenging to integrate the reliability analysis with durability optimization. For efficient evaluation of durability design constraints, a preliminary crack initiation fatigue life analysis is carried out to identify critical spots with short fatigue life. The result of this analysis is used to define the design constraints. A refined durability analysis is then carried out at these critical spots to obtain an accurate measurement of fatigue life. Various model uncertainties such as geometric tolerance and material properties are taken into account to predict uncertainties of the structural durability through advanced reliability analysis. Consequently, the envisioned CAD-based process is developed by integrating the proposed, effective RBDO method with a systematic durability analysis, with emphasis on numerical efficiency and accuracy.

2C-4 **Efficient Evaluation Approaches for Probabilistic Constraints in Reliability-Based Design Optimization**
Byeng-Dong Youn, KK Choi

With extensive efforts in various engineering disciplines over last three decades, design guidelines and/or standards have been or are being modified to incorporate the concept of uncertainty into the product design. In response to these new requirements, various methods have been developed to treat uncertainties in engineering design and, more recently, to carry out design optimization with additional requirement of reliability. The latter is referred to as reliability-based design optimization (RBDO). The objective of this presentation is to develop efficient evaluation methods for probabilistic constraints in RBDO to substantially improve computational efficiency when applied to large-scale applications. Two different methods will be presented: efficient identification of feasible probabilistic constraints and efficient reliability analysis using the condition of design closeness. Unlike deterministic design optimization, a significant computational burden is imposed on feasibility check of constraints in the RBDO process due to expensive reliability analysis. Such difficulties can be effectively resolved by using a mean value (MV) first-order method with an allowable accuracy for the purpose of feasibility identification, and by carrying out the refined reliability analysis using the hybrid mean value (HMV) first-order method for e-active and violate constraints in the RBDO process. Some of the information obtained at the previous RBDO iteration is reused to efficiently evaluate probabilistic constraints at the current design iteration using the design closeness. To demonstrate numerical efficiency of the new RBDO process, several numerical examples, including a large-scale multi-crash application, are shown.

2D Vehicle-Terrain Interaction Modeling & Simulation

2D-1 **Interaction between a pneumatic tire and snow**
Tinggang Zhang, Jonah Lee, Douglas Goering, Chuen-Sen Lin, Sally Shoop, Mike Letherwood Presenter: Jonah Lee and Tinggang Zhang

The study of the interaction between a pneumatic tire and deformable terrain such as unpaved ground or snow has a great impact on the design and dynamic performance of an off-road vehicle. The general-purpose finite element program, ABAQUS, was used to conduct the simulation and to calculate the tire forces as a function of longitudinal slips, slip angles and slips with a camber angle. As far as the authors are aware, this is the first time that simulation of tire/snow interaction has been conducted where tire forces have been calculated as a function of lateral slip angles. Two tire models were studied in the current project. The first is a rigid tire on fresh snow in which the whole tire is modeled as a rigid body. The second is a deformable tire on fresh snow, in which the tire is modeled as a composite material made of rubber (hyperelastic material with viscosity) and reinforced plies of steel bar with a rigid rim. The fresh snow is modeled as an elastic-plastic material characterized by a cap Drucker-Prager model. The analysis results are expressed as the tire forces versus longitudinal slip or slip angle. The numerical results are compared with the available experimental data.

2D-2 **Simulation of vehicle dynamics with tire/ground interface using Simulink**
Chuen-Sen Lin, Prasana Kumar Saitana, Tingang Zhang, Jonah Lee, Douglas Goering, Sally Shoop, Mike Letherwood Presenter: Chuen-Sen Lin

The purpose of this work is to develop a dynamic simulation program to predict the dynamic behavior of vehicles, including tire and cold region terrain interface. Other concerns of this work include computation speed and accuracy for potential real time applications and modeling methods for continuous improvement of the component models and the avoidance of accumulated errors for long-term simulations. The current status of this work is at its beginning stage. This presentation will discuss the preparation work, which has been done, for the development of the simulation program, the up-to-dated development results, and the planed future work. The preparation work includes the selection of an appropriate language tool for the development of the computer simulation program, the investigations of computation speeds and reliabilities of selected mathematical vehicle component models including vehicle model and tire/terrain models of both rigid and deformable terrain, studies of possible improvements needed for the selected models, the design of the structure of the expected simulation program, and the consideration of potential means to avoid accumulated errors for long-term simulations. Presently, a Matlab/Simulink computer model has been developed and the model includes vehicle sprung and unsprung masses and tire/terrain interface. The developed model currently only simulates coupled forward, heave, and pitch motions. The targeted model will include roll, pitch, yaw, heave, forward motion, and transverse motion.

2D-3 **High Fidelity Vehicle-Terrain Interaction Modeling and Simulation**
W. Pan*, L.-D. Chen, and D. Solis, University of Iowa

Due to the complex nature of tire-terrain interaction, real-time vehicle-terrain interaction simulation has so far resolved to use either the overly simplified theoretical tire-terrain interaction models or empirical models that are heavily dependent on experimental data that are usually expensive to collect. The purpose of developing high fidelity tire-terrain model is threefold. First, parameters in empirical models can be identified via virtual tests using high-fidelity models, hence reducing the degree of dependency on experimental data. We will present virtual test methods that enable us to generate parameters in our real-time tire-soil interaction model reported in the 2002 ARC conference. An example of real-time simulation of a HMMWV traveling on different soils, whose parameters are identified, using a high-fidelity model, will be presented. Secondly, high fidelity models aid the development of more elaborate and/or new real-time simulation models. This is because, compared to lab testing, virtual testing using high-fidelity models is much more versatile, allowing more accurate and more complex control over test conditions, reporting detailed information that a lab can not possibly collect. An example of using a high-fidelity model to create real-time model will be presented. Finally, by integrating with a full vehicle model, high-fidelity tire-terrain interaction model enables high-fidelity full vehicle-terrain interaction simulation. This is an important step towards accurate assessment of vehicle mobility on a deformable, adverse terrain environment. An example of a high-fidelity HMMWV running over rough terrain will be presented.

2D-4 **Tracked Vehicle Dynamic Simulation: Robot Vehicle and Real-Time Simulation**
D. Akcabay, J.H. Lee, Z.-D. Ma, N. C. Perkins*, University of Michigan

This presentation will summarize advances made in simulating tracked vehicles. The first advance concerns the mobility of small-scale robotic vehicles that employ tracks as the running gear. Simulation studies will be reviewed to highlight the major factors that limit the mobility of tracked robotic vehicles on both smooth and rough terrain surfaces. An example rough terrain surface is a staircase, and an example smooth terrain surface is a hill with continuously increasing slope. The second advance concerns the modeling approximations needed to generate real-time simulations of tracked vehicles on soft terrain. We will review the approximations needed to capture the physics of track-terrain interaction, track dynamics, vehicle dynamics (sprung and suspension components) as well as terrain topology and terramechanics. These elements are incorporated in real-time simulations of an example two-wheeled vehicle.

Symposium III

3A Fuel Cell Power

3A-1 **Instrumentation Acquisition and Development of a Fuel Cell Control Laboratory**
Stefanopoulou

Leveraging funding from the National Science Foundation (NSF) we developed a Fuel Cell laboratory with instrumentation and equipment for the design and verification of Control and Diagnostic Algorithms for Fuel Cell Power Systems. The experimental set-up allows the implementation of multivariable controllers, fault detection, and diagnostic algorithms for the regulation of reactant flow and pressure, stack temperature, and membrane humidity. It is anticipated that the development and testing of real-time control and diagnostic systems will accelerate the use of Fuel Cells by enhancing their safety, increasing their efficiency, and ensuring their robustness in real world applications.

3A-2 **Control of Fuel Cell Breathing: Addressing the Oxygen Starvation Problem**
Stefanopoulou

One of the critical control problems in Fuel Cells is to effectively regulate the oxygen concentration in the cathode by quickly and accurately replenishing oxygen depleted during power generation. The features and limitations of different control configurations and the effect of various measurement on the control performance are examined. For example, an observability analysis suggests using the stack voltage measurement as feedback to the observer-based controller to improve the closed loop performance.

3A-3 **Assessing Model Range of Validity: A Fuel Cell Case Study**
Bryon Sohns

The ability to quantify the Range of Validity of a model is essential to ensuring accurate simulation-based design. "Range of Validity" refers to a) bounds on the inputs to the system from the environment within which the model has acceptable predictive value, and b) the space of parameter values - design points - in which the model accurately predicts system behavior. An initial approach to quantifying Range of Validity with respect to inputs is presented based on an extension of earlier Thrust Area 1 work on determining model validity. Preliminary results show the feasibility of the approach as applied to an illustrative mass-spring-damper model and to an empirical nonlinear fuel cell model from a current ARC project. The results show the range within which the controller can vary fuel cell stack current for a given control system design model. Outside this range the model has quantitatively unacceptable predictive ability. If the controller is found to exceed the validity bounds then a new controller must be designed based on a higher-fidelity model, or the accuracy tolerances must be reconsidered. Future work will extend the Range of Validity to the model parameters as well as inputs, and to simulation models that must predict measured data from real systems. Connections to other ARC projects include mapping the input or design space over which model partitions exist, or ensuring that a given simulation model is valid over the expected range of variation of uncertain design parameters.

3A-4 **Thermal Modeling of PEMFC**
Sangseok Yu

Numerical simulation of PEMFC including 2-D heat transfer model and agglomerate model of cathode catalyst layer is developed. The simulation has the capability of predicting heat and humidity effects on fuel cell performance due to the heat transfer model combined with the models of membrane resistance and cathode overpotential. The membrane resistance model employed water transport through membrane well explained trends of humidity effects of PEMFC. In addition, cathode overpotential modeling with agglomerate model of cathode catalyst layer showed trend of rapid drop observed by experiments when PEMFC was operated at high current density regions.

3B Hybrids & Powertrain Electrification

3B-1 **Modeling of Electric Acessories and Fuel Cell APU for the FMTV Truck**
Loucas Louca, Zoran Filipi, Burit Kittirungsi, Chan Lee, Huei Peng, Jay Pukrushpan, Anna Stefanopoulou

The reduction of parasitic losses is an important milestone on the road to future highly efficient trucks. Current trucks, depending on the duty cycle, may have parasitic losses that account for up to 45% of the total energy losses. Hence, compounding the techniques for reducing parasitic losses with the use of advanced diesels and hybrid propulsion systems holds a promise of achieving the aggressive fuel economy goals set by the Future Combat Systems and the 21st Century Truck initiatives. This work investigates the potential to reduce parasitic losses on the hybrid medium tactical truck (FMTV) through electrification of accessories. The electrified accessories are decoupled from the engine for more efficient operation and the electric power for these accessories is provided by a Fuel Cell APU. The engine oil pump, power steering pump, air compressor, and air conditioning compressor are selected for electrification.

This study focuses on the modeling of the accessories and the Fuel Cell APU. Good models are critical for providing accurate predictions of power consumption and fuel economy. The engine, drivetrain, and vehicle dynamics models of the FMTV truck are previously developed using the Vehicle Engine Simulation (VESIM). The VESIM environment is also used for the development of the accessories models. Different complexity models are used depending on the engineering requirements. In addition, the Fuel Cell APU model is based on a detailed nonlinear model and experimental data. Finally, representative and realistic duty cycles for the accessories are developed in order to provide accurate power consumption predictions. The dynamic analysis and fuel consumption of the proposed configuration are discussed in the companion presentation (Reduction of Parasitic Losses of the FMTV Truck through Electrification).

3B-2 **Reduction of Parasitic Losses of the FMTV Truck through Electrification**

Zoran Filipi, Burit Kittirungsi, Chan Lee, Loucas Louca, Huei Peng, Jay Pukrushpan, Anna Stefanopoulou*

The reduction of parasitic losses is an important milestone on the road to future highly efficient trucks. Current trucks, depending on the duty cycle, may have parasitic losses that account for up to 45% of the total energy losses. Hence, compounding the techniques for reducing parasitic losses with the use of advanced diesels and hybrid propulsion systems holds a promise of achieving the aggressive fuel economy goals set by the Future Combat Systems and the 21st Century Truck initiatives. This work investigates the potential to reduce parasitic losses on the hybrid medium tactical truck (FMTV) through electrification of accessories. The electrified accessories are decoupled from the engine for more efficient operation operation and the electric power for these accessories is provided by a Fuel Cell APU. The engine oil pump, power steering pump, air compressor, and air conditioning compressor are selected for electrification.

The study examines the behavior of accessories during the driving schedule and the reduction of the total accessory energy consumption due to accurate control. Next, we analyze in detail the energy conversion options on the system level, e.g., the effect of decoupling accessories from the engine on its average efficiency, the effect of using of Fuel Cell APU vs. the alternator, etc. The results provide clear direction for future work on further electrification and practical implementation of advanced accessories. The modeling and duty cycles of accessories are discussed in the companion presentation (Modeling the Fuel Cell APU and Electric Accessories for the FMTV Truck).

3B-3 **Field Investigation of Military Hybrid Vehicle Performance**

Doug Goering

The U.S. Army's Cold Regions Test Center (CRTC) is presently field testing the second generation Hybrid Electric High Mobility Multipurpose Wheeled Vehicle (HE-HMMWV) produced by AM General and PEI. Data from a preliminary model of this vehicle constructed with PSAT, Simulink, and Matlab have previously been presented. The model has been refined and results from the simulated HE-HMMWV performing a standard drive cycle will be presented. Actual data from test runs of the vehicle at CRTC will also be presented. Finally, use of the vehicle test data as a means of calibrating and improving the simulation model will be discussed. A fully calibrated model will allow predictions of vehicle performance under extreme conditions that may not be attainable with the actual vehicle due to time or environmental constraints.

3C Diesel Spray, Combustion and Heat Transfer

3C-1 A New Model for Combustion and Emissions in High Speed Diesel Engines

N. A. Henein

A new phenomenological model is developed for the combustion process and engine-out emissions in small-bore, high-speed, direct-injection diesel engines. The model describes the fuel distribution in the combustion chamber taking into consideration the interaction between the spray and gas motion including the swirl and squish components. The fuel is divided into parts that behave differently. These include the fuel part injected before the flame is established in the combustion chamber, the part injected in the flame and that deposited on the walls. The model examines the effect of different engine operating variables on the combustion of different fuel parts and their contribution in engine-out emissions. Emphasis is made on the trade-off between NOx and soot emissions. The model predictions are compared with experimental data obtained on a single-cylinder research engine, equipped with a common rail injection system, running under simulated turbocharging conditions. The experiments covered a wide range of speeds, loads and EGR ratios.

3C-2 Simulation of Fuel Injection Dynamics and High-speed Fuel Spray

Ming-Chai Lai

High-pressure injection system remains a key core technology for advanced high-power-density engine or advanced APU for hybrid powertrain. There are three levels of simulations: the hydraulic simulation for the injection system dynamics, and the internal flow for the nozzle fluid dynamics, and external spray simulation for the fuel-air mixing dynamics. These simulation tools have been used as a predictive design tool with different degrees of success. However, due to the advances of recent engineering technology, the simulations still face many challenges to simulate the complicated physical processes involved. Using high-pressure direct-injection diesel injection system as examples, the current work examines the capabilities and challenges of these simulation tools. Hydraulic simulation is carried out to predict the injector dynamics of EUI, HEUI, and HPCR injectors. The internal CFD simulation investigates the effects of nozzle geometry and cavitation model on the predictions of advanced VCO and mini-sac nozzles. A new external CFD simulation is carried out to simulate the potential spray shock interactions in HPD and HCCI applications. Favorable agreements are demonstrated with experimental results taken at WSU.

3C-3 Development of Diesel Engine Emissions and Performance (DEEP) Model for Engine-in-vehicle Simulation

Dohoy Jung, Loucas Louca, Zoran Filipi, Dennis Assanis, Jeffrey Stein

A reduced multi-zone combustion model is developed to improve computational efficiency of the previously developed full size multi-zone combustion model which is based on quasi-dimensional approach. The reduced model maintains the capability of predicting engine performance and emissions as the original model. It is modified and implemented into SIMULINK based engine sysytem simulation and integrated with drivetrain and vehicle dynamics models for the transient vehicle behavior case studies.

3C-4 Development and Validation of Unsteady Convective Heat Transfer Correlation

Pin Zeng

The analytical tools widely used for estimating convective heat transfer coefficient in the engines are correlations in the form of or which differ only by the empirically fitted constants a, b and n. These correlations provide reasonable agreement with experimental data in fully developed steady pipe flows and acceptable agreement with time-resolved experimental data in unsteady flows with slow velocity and temperature variations.

However, for highly unsteady flows with rapid velocity and temperature variations, these correlations can produce large errors in both phase and amplitude. In this study, first, two dimensionless variables are found to represent the effects of the velocity and temperature variation on the convective heat transfer through dimensional analysis. Second, a dynamic variable concept is proposed to use these two dimensionless variables to extend the steady correlation to a unsteady correlation. The new correlation indicates that the time-resolved unsteady heat transfer coefficient is not only the function of Reynolds (and Prandtl) number, but also the function of changing rates of the velocity and temperature. At the limit of steady flows, the unsteady correlation collapses to the steady correlation. The experimental results from engine tests are used to validate the new unsteady correlation. The comparison between the experimental results and the prediction shows good agreements.

3D Modeling Engine Processes and Systems

3D-1 High Power Density Diesel Cycle Simulation

N. Chalhoub

The focus of this work is to develop a tool that can facilitate the design process of high power density Diesel engines to be used in future military and commercial applications. To achieve this goal, an extensive research effort has been devoted at Wayne State University to develop a user-friendly, MATLAB/Simulink-based, generic simulation code to assess the performance of advanced high power density diesel engines under both transient and steady-state modes of operation. The model consists of a series of physics-based and experimentally verified sub-models for the various engine processes and components. It takes into consideration the processes inside the intake and exhaust systems, processes inside the cylinder, the dynamics of the crank-slider mechanism and the engine frictional losses. Furthermore, implementing a reduced chemical kinetics model will provide the instantaneous concentrations of different species during the combustion process. Digital simulation results will be shown to illustrate the capabilities of the simulation tool.

3D-2 Variable Geometry Turbocharging for Enhanced Performance and Transient Response - a Retrofit Study

Chad Jagmin

The U.S. Army's aging diesel fleets are lagging in both performance and emissions standards. It is difficult for many of the older diesels (up to 22 years) to keep up with the rest of the more modernized fleets of vehicles and pieces of equipment. The two technologies of variable geometry turbochargers (VGT) and exhaust gas recirculation (EGR) have shown promise in numerous and varied tests to maintain or improve performance and emissions. Although many initial tests on the coupling of these systems were on new, single-cylinder, and mostly high-speed passenger car applications, the results of these tests are promising. An in-depth study of performance and emissions of a slightly-aged, multi-cylinder (production), heavy-duty diesel application is performed at a speed of 1200 RPM and a 30% requested load. The results of the initial experimental engine tests are promising. Although the two technologies do not eliminate heavy-duty emissions, they both have limited uses in ! the realm of NOx for EGR and most emissions products for VGT. In general, the emissions reductions come at a compromise to performance. Thus, the application of VGT and EGR to a heavy-duty diesel engine is limited to lower load conditions, where the operator of the engine does not require maximum performance from the engine. VGT tests show significant performance gains in lower speeds resulting in better acceleration and drivability for the operator. Implementation of EGR has considerable packaging and cost issues. On the other hand, implementation of VGT could be relatively easy with the retrofit of the VGT and an upgrade to the electronic control module.

3D-3 **Development of an EDC-based Combustion Model for Diesel Combustion**
S. Hong, D. N. Assanis, M. S. Wooldridge and H. G. Im

In diesel engine combustion, combustion is most likely to occur in the flamelet regime where chemical reaction is confined within a thin layer where the fuel and oxidizer meet. The length scale of the thin reaction zone is often smaller than the spatial resolution used in many computational simulations, e.g. KIVA models. However, the characteristics of flamelet combustion should be properly modeled to represent the combustion process accurately. The eddy dissipation concept (EDC) has been widely used in simple combustion systems such as co-flow or counter-flow configurations, due to the enhanced accuracy in predicting reaction rates compared to conventional simplified combustion models like the eddy break-up (EBU) model. The EDC model allows more realistic characterization of the sub-grid scale combustion phenomena within the thin reaction zone as well as the small-scale molecular mixing processes. In addition, the model can easily incorporate detailed chemistry. Despite the advantages, the EDC model has rarely been applied in predicting diesel combustion phenomena due in part to difficulties in implementation in large numerical codes. In this study, a combustion model based on the EDC model is developed and used to predict combustion rates in diesel engines. Results predicted using the EDC-based combustion model show good agreement with experimental data, demonstrating the potential of the model as a predictive tool for the diesel engine development.

3D-4 **Two-Dimensional Effects in the Lubrication of the Cam Tappet Contact**
D. Taraza

The cam-tappet contact experiences very high loads and the lubrication conditions are Elasto-Hydrodynamic (EHD). In EHD lubrication the oil film thickness (OFT) is mainly determined by the entrainment speed of the oil and the oil viscosity. Under the high load present in the cam-tappet contact the OFT reaches very small values in the order of magnitude of a fraction of one micrometer and asperity contacts cannot be avoided. In this situation the friction force has two components, a boundary and a viscous one, and non-Newtonian behavior of the oil prevails. The friction force is determined by the rheological properties of the oil and the geometry of the contact (combined radius of curvature, cam width and combined asperity of the rubbing surfaces). For valve trains with bucket type tappets, the mechanism is design to rotate the tappet during engine operation to assure a uniform wear of the tappet surface. Under such operating conditions, both the entrainment speed and the radius of curvature are varying along the contact patch determining variations in the OFT and, consequently, variations in the ratio of the boundary friction component along the contact patch. Based on a simulation model that considers the tappet spin under the action of the friction force between cam and tappet and the friction force between tappet and its bore, the entrainment speeds and their angle are calculated along the contact patch. The different angles of the entrainment speed determine different values of the radius of curvature and the OFT variations along the contact patch may be calculated. It was found that the boundary friction component reaches a maximum value at the outer edge of the cam during the valve-closing event. Because the boundary component of the friction force is mainly responsible for wear it is expected to see an increase in wear at this region of the cam around the cam nose. Optical inspection of a camshaft that has worked several hundred hours in a single cylinder diesel engine seems to confirm this finding.

Symposium IV

4A Multilevel Systems Optimization

4A-1 **Using Discrete-Event Simulation Tools to Specify and Implement Coordination Strategies in Multilevel Systems Optimization**
Michael Kokkolaras

We use the computer science language “Chi” to specify and implement alternative coordination schemes of the Analytical Target Cascading (ATC) process. Chi has been developed originally to model discrete-event simulations of manufacturing processes at the Eindhoven University of Technology, and is based on concepts of Communicating Sequential Processes (CSP). We show that a concurrent programming language such as Chi can facilitate and improve the implementation and testing of multilevel optimization coordination strategies. Specifically, ATC is implemented as parallel processes that exchange data via channels, which represent the links between the subproblems. Coordination-specific instantiations define how individual processes communicate with each other. We demonstrate the advantages of Chi for coordinating the ATC process by means of an illustrative example.

4A-2 **Multilevel Systems Optimization under Uncertainty**
Michael Kokkolaras

When designing a complex engineering system while taking into account the stochastic nature of design variables and input parameters, the variation in the outputs of interest due to variations of the inputs cannot be quantified accurately because the uncertainty is propagated through a highly nonlinear system. In this case, it may be beneficial to decompose the system into a multilevel hierarchy of subproblems and investigate the propagation of uncertainties throughout this hierarchy. To accomplish that, we have reformulated the Analytical Target Cascading (ATC) process as a reliability-based design optimization framework, and have adopted a linearization technique to determine statistical properties of the propagated random quantities. We present the probabilistic formulation of ATC and demonstrate the mentioned technique for uncertainty propagation by means of an automotive engine subsystem example.

4A-3 **Lagrangian Coordination for Large-Scale Systems Revisited**
Julie B. Lassiter, Margaret M. Wiecek, Kara R. Andrighetti and Vincent Y. Blouin

The goals of this on-going effort are to find a convergent algorithm for general non-convex decomposed problems and to develop an intelligent mechanism for determining objective function weights on discrepancy/coupling terms. In this research we use Lagrangian duality to solve large-scale nonlinear problems and propose several decomposition and coordination methods in which iteratively and concurrently solving subproblems leads to a solution of the original problem. We include an extension to multiple level problems with multiple subsystems on each level, present the corresponding algorithms - incorporating subgradients and cutting-planes to achieve said solution - and demonstrate with examples.

4A-4 **The Step after Analytical Target Cascading: Analytical Target Setting**
Panayiotis Georgiopoulos

The Automotive Research Center expertise in high-fidelity simulation of ground vehicle concepts enabled Thrust Area V to support technical decision-making analytically. Here we demonstrate how ARC expertise can be leveraged to support enterprise decision-making. Assuming a compartmentalize hierarchical enterprise we quantify the high-level trade-off among customer satisfaction, product development and manufacturing costs and product performance. This quantification allows us to formulate the analytical target setting model. The solution of this decision model are product performance targets which are set to the engineering supersystem organizational level and then cascaded to engineering systems and subsystems across the product development organization. The effectiveness of linking analytical target setting and cascading is discussed in an automotive truck vehicle example.

4B Simulation Environments

4B-1 **A Gluing Algorithm for Distributed Simulation Of Multibody Systems**
Jinzhong Wang

A new gluing algorithm is presented that can be used to couple subsystem models for dynamics simulation of mechanical systems. The gluing algorithm developed relies only on information available at the subsystem interface. This strategy not only improves the efficiency of the algorithm, but also engenders model security by limiting model access only to the exposed interface information. These features make the algorithm suitable for a real and practical distributed simulation environment.

4B-2 **Vehicle Modeling and Simulation Environment for Off-Road Applications**
Dario Solis

This presentation covers the use of the multi-body approach in modeling vehicles for the vehicle dynamic analysis during off-road maneuvers. A number of equivalent models are presented, with an explanation of how these model variants affect computational cost and the model's ability to predict the physical system performance. The High Performance Dynamics Code (HPDC) environment, from the University of Iowa, is used to implement the models and carry out the simulations. This environment also showcases recent advances in numerical methods and tire-soil interaction models developed by the University of Iowa's NADS ARC team.

4B-3 **Solving the Acceleration Equations Using a Projection Method**
Dale Holtz

Solving the acceleration equations is the most expensive operation for real-time simulation using the Cartesian formulation. The coefficient matrix for the acceleration equations is large and sparse and the efficiency of the solution is greatly affected by topology of the model. Typically the topology of most vehicle models looks like a star pattern, several bodies attached to one central chassis body. As more wheels are added, as occurs with many military vehicles, more bodies are attached to the chassis body. Current methods implemented in the High Performance Dynamics Code (HPDC) are inefficient for models with star topologies. Therefore a new method has been created that is more suitable for star topologies. This method uses the efficient topology based Jacobian factorization, developed in previous ARC work, to project the acceleration equations onto a set of independent variables. Results show that this new method is significantly faster than previously implemented methods for models with star topologies.

4C CAE Methodologies, Thermal Signature

4C-1 **Signature Analysis of Vehicles and Automotive Components Using Thermal Imaging and 3D Information**
David Page, Andreas Koschan, Mongi Abidi

In this research, we investigate the integration of thermal data with 3D geometry data. This investigation includes test data collected from scans underneath vehicles and simulation data generated from software. We collect the test data using a low-profile robotic platform equipped with thermal and visual video cameras. For each video image sequence, a fundamental component of this research is a multi-perspective mosaic technique that allows stitching of these sequences into a single image. We present the theory and results of this technique, and we show results for the data collection and simulation stages, as well.

4C-2 **Virtual Thermal Management Design and Evaluation**
Jay Ochterbeck, Keith Johnson, Paul Rogers

Innovative tools for vehicle subsystem design, thermal management, and infrared signature prediction are being developed to provide support for rapidly analyzing the cost and signature impacts of design decisions. Proper thermal management increases the performance, efficiency, survivability, and reliability of vehicles. With the thermal and infrared simulation capability of MuSES engineers can optimize and efficiently evaluate their designs using real world scenarios. The thermal management, performance, and efficiency advantages for military vehicles apply to commercial vehicles and systems as well. Commercial benefits include the ability to optimize vehicle designs in achieving reduced fuel consumption and emissions. The thermal management techniques also have overlap to other disciplines including electronics cooling systems, aircraft and spacecraft. Manufacturers of thermal management components greatly benefit from the ability to predict product performance when integrated into a vehicle design. In order to provide mapping from component level to full system scales, techniques are required to ensure accurate prediction of component behavior but not so much detail as to be computationally limiting to system level models. This work focuses on providing thermal fluid design tools that allows rapid thermal design and simulation from the individual components to the entire vehicle.

4C-3 **Shell Extraction of 3D CAD models for Packaging applications**
Mr. Miao Yi, Dr. G. Fadel

In order to apply packaging techniques to real problems, the CAD components must be directly interfaced to the optimizer. The difficulty encountered is that the CAD models are very detailed 3D shapes with internal features that are irrelevant in the packaging application. This talk will describe the difficulties encountered, and the development of an algorithm that automatically extracts the exterior shell of a complex assembly in the STL format. That format is used since it is a common standard used in all CAD systems, and furthermore, computations on the tessellated model (STL) are much more efficient for the optimization interface and for distance calculations.

4C-4 **Multi-Objective Configuration Optimization with Vehicle Dynamics Applied to a Mid-Size Truck**
Mr. Miao Yi, Dr. V. Blouin, Dr. G. Fadel, Dr. I. Haque

Most engineering problems require optimizing several design objectives that compete with each other. We will present a configuration optimization method using a multiple objective genetic algorithm. It has been applied to a midsize truck configuration optimization problem, in which two objectives are considered: dynamic behavior (single metric incorporating multiple performance indices) and ground clearance. Parallel computation technology is also incorporated to accelerate the optimization process as running the vehicle dynamics model is very time consuming.

4D Automotive Product Development

4D-1 **An Enterprise Decision Model for Optimal Vehicle Design and Technology Valuation**
Adam Cooper

Design optimization traditionally deals with engineering design decisions. Yet it is well understood that optimal product decisions must be based on engineering as well as marketing and production considerations. An Enterprise Decision Model attempts to link these aspects of the product development enterprise so that the value of the designed product to the enterprise can be assessed. The model also values new product technology in accordance with the enterprises current operations to increase the likelihood of commercialization success before committing to a new strategy. Dual-use synergies between a commercial enterprise and the Army are also considered for new technology development to investigate the impact of the Armys acquisition process on product design decisions. The valuation technique uses comprehensive engineering simulation to provide a preliminary understanding of the technologys market and design potential. The model represents the enterprise in a mathematical formulation that simultaneously optimizes initial product design, product pricing, operating costs associated with capacity allocation and design decisions, and the value created by new products. The Enterprise Decision Model is demonstrated for optimal vehicle design in the medium truck market, experiencing hybrid penetration.

4D-2 **Efficient Product Portfolio Reduction**
Ryan Fellini

A product portfolio can be defined as the set of artifacts marketed by a corporation in order to meet its customer's needs. The proliferation of products in a company's portfolio can create inefficiencies due to the greater complexity and the corresponding effort required to design and manufacture the set of products. A methodology for efficiently reducing the number of products through the use of an extended commonality strategy is presented in this article. The proposed design process allows for an efficient merging of the individual product designs. The result is a portfolio that is reduced in absolute size and has maximum commonality between the remaining products. The methodology is applied to the design of various automotive systems.

4D-3 **A Study of Emission Policy Effects on Optimal Vehicle Design Decisions**
Jeremy Michalek

A methodology is presented for studying the effects of automobile emission policies on the design decisions of profit-seeking automobile producers in a free-entry oligopoly market. The study does not attempt to model short-term decisions of specific producers. Instead, mathematical models of engineering performance, consumer demand, cost, and competition are integrated to predict the effects of design decisions on manufacturing cost, demand, and producer profit. Game theory is then used to predict vehicle designs that producers would have economic incentive to produce at market equilibrium under several policy scenarios. The methodology is illustrated with three policy alternatives for the small car market: corporate average fuel economy (CAFE) regulations, carbon dioxide emissions taxes, and diesel fuel vehicle quotas. Interesting results are derived, for example, it is predicted that in some cases a stiffer regulatory penalty can result in lower producer costs because of competition. This mathematical formulation establishes a link between engineering design, business, and marketing through an integrated optimization model that is used to provide insight necessary to make informed environmental policy.

4D-4 **Multi-Scenario Multi-Criteria Optimization in Engineering Design**
Vincent Blouin, Margaret M. Wiecek, Vijay Singh

Motivated by applications in engineering design, a mathematical model of the multi-scenario multi-criteria optimization problem is introduced. Theoretical results for the single-scenario case are presented to support a solution methodology developed for the bi-scenario bi-criteria case. Mathematical and structural examples are included.