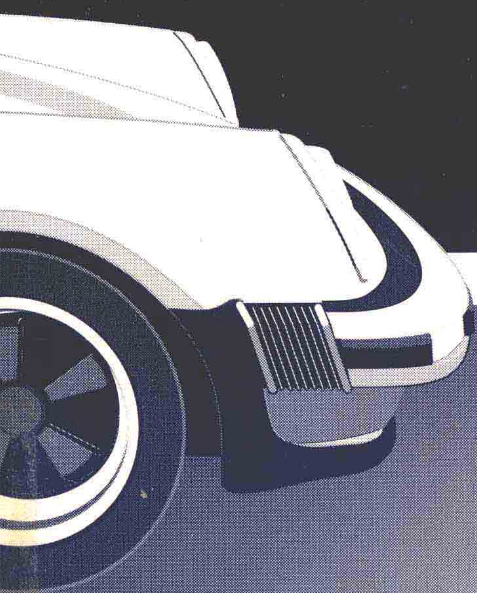
VEHICLE-ROAD INTERACTION

Bohdan T. Kulakowski

EDITOR



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Bohdan T. Kulakowski, Editor

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Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

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Foreword

This publication, *Vehicle-Road Interaction*, contains papers presented at the Vehicle-Road Interaction II conference held in Santa Barbara, California on 17–22 May 1992. The conference was sponsored by the Engineering Foundation (related ASTM Committees are D-4 on Road and Paving Materials and E-17 on Pavement Management Technologies). Bohdan T. Kulakowski of Penn State University presided as symposium chairman and was editor of this publication.

Contents

Ride Quality and Road Roughness

Advances in Vehicle Suspension Design and Control

Noise Emission Due to Vehicle-Tire-Road Interaction

Fuel Efficiency and Rolling Resistance

Overview

Most of the problems associated with the safety, economy, and overall quality of road transportation are affected by the characteristics of both roads and vehicles and by the manner in which these two dynamic systems interact. In spite of the complex interaction between roads and vehicles, there has been little interaction and a rather limited flow of information between road and vehicle researchers. At most professional meetings and conferences, the emphasis is usually placed either on roads or on vehicles, but very rarely on both. Moreover, in those conferences that do include both road and vehicle topics in their programs, the road and vehicle presentations take place in separate and often concurrent sessions. In 1990, the first Vehicle-Tire-Pavement Interface Conference was conducted by the Engineering Foundation. In this conference, equal emphasis was placed on the vehicle and the roadway. In 1992, the second Engineering Foundation conference on Vehicle-Road Interaction was held at Santa Barbara, California. This special technical publication has been published as a result of the Vehicle-Road Interaction II Conference in an effort to communicate the current state of the art and future research needs to those involved in studies of vehicles and roads.

The 16 papers published in this volume can be grouped into seven subject areas. These areas are: modeling and simulation of vehicle dynamics and vehicle-road dynamic interaction, laboratory and field tests of vehicle-induced pavement loading, tire characteristics, ride quality and road roughness, advances in vehicle suspension design and control, noise emission due to vehicle-tire-road interaction, and fuel efficiency and rolling resistance.

Modeling and Simulation of Vehicle Dynamics and Vehicle-Road Dynamic Interaction

There are four papers in this section. The first paper, by Verheul et al., presents a general-purpose computer simulation program, called BAMMS, developed from the bond graph model of multibody systems. The features that set BAMMS apart from many other vehicle simulation programs are its flexibility and expandability to a great variety of dynamic systems that can be modeled using bond graphs. Two applications of the program are described; one is the analysis of performance and optimization of design of a racing truck, and the other is the investigation of stability of tractor-trailer combination.

Two other papers in this section deal with computer simulation of the dynamic tire forces of heavy trucks, which constitute a very important element of vehicle-road interaction. The dynamic tire forces of heavy vehicles are the primary cause of pavement damage and have become the subject of many research studies in recent years. However, only a few computer models, of many that have been developed in those studies, have been validated using experimental data. The paper by Cole and Cebon describes a nonlinear three-dimensional model of a heavy vehicle and the results of an experimental validation study. In general, very good agreement was found between measured and calculated tire forces. The three-dimensional model was then compared with a two-dimensional model. The authors concluded that the two-dimensional model is satisfactory for predicting tire forces of typical leaf-sprung, articulated vehicles operating under typical conditions of speed and road roughness. Huhtala et al. used a commercial multibody system analysis software, called ADAMS, to simulate tire forces generated by three-axle and four-axle trucks. The paper provides a thorough analysis of the results of computer simulation. Experimental validation of the truck models is planned for the near future when data from tire force measurements become available.

The fourth paper, authored by Gillespie and Karamihas, uses analytical relationships between truck properties and pavement damage to determine which truck characteristics have the strongest effect on pavement damage. The truck characteristics studied included truck type, axle loads, number of axles, spacing between axles, suspension type, and tire parameters. Static axle loads were found to have the strongest effect on pavement damage.

Laboratory and Field Tests of Vehicle-Induced Pavement Loading

The two papers published in this section deal with laboratory devices used for accelerated testing of pavement response to vehicle loading. The first paper, by Hugo, focuses on the design of the Texas mobile load simulator, whereas in the other paper, Krarup reports results from tests conducted on the Danish road testing machine. The expected dynamic performance of the Texas simulator was investigated using computer simulation. Two 1:10 scale models of the simulator were then built and tested to augment the design of the full-scale machine.

Krarup's paper can serve primarily as a source of relevant technical data including pavement stress and strain distributions measured under two types of loads, rolling truck tire and falling weight deflectometer. The interpretation and conclusions from the test results are left up to the reader to consider.

Tire Characteristics

This section includes two papers. In the first paper, Gelling describes the tire tread properties and their effect on traction, rolling resistance, and wear. Tire traction, rolling resistance, and wear are known to depend on tire construction and road surface texture characteristics. Gelling shows that these tire properties can also be related, to some extent, to viscoelastic properties of the tread material. In addition, the paper raises an issue of environmental effects of tire properties. Tire recycling and vehicle/tire contribution to the greenhouse effect are two major areas of concern to the tire and automotive industries.

The paper by Navin presents a skid resistance case study conducted on a surface treated with a pavement rejuvenator using a 1991 Lincoln Town Car equipped with an antilock brake system (ABS). The main difficulty in traction tests involving ABS-equipped vehicles is determining when and where the braking actually starts and stops. The testing procedure described by the author should be of interest because it offers an economic alternative to an expensive skid trailer.

Ride Quality and Road Roughness

Ride quality is an important aspect of vehicle-road interaction, not only as a matter of comfort but, more importantly, as a factor affecting driver fatigue and thus traffic safety. Ride quality is a subjective quantity based on a level of comfort perceived by persons traveling over a selected section of road. Since obtaining subjective ratings of ride quality is a rather involved and costly process, highway engineers developed objective measures calculated from road profile and/or vehicle response data to estimate the ride quality. Spangler and Kelly compared five different measures of ride quality that are in common use today, and found the Ride Number to be superior to the other measures in this group. The Ride Number is derived from the road profile measurements, then processed with a digital filter that emphasizes the range of wavelengths to which human subjects have been found to be most sensitive while traveling in highway vehicles.

The paper by Gilmore, while concentrating also on objective evaluation of ride quality, introduces a ride quality measure derived from the dynamics of interaction between a rider and a seat. A new computer program is presented that can be used to simulate the rider-seat interaction. The program can also be employed as a tool in seat and vehicle design. A new feature of the program is that it includes nonlinearities due to geometry or changing kinematic constraints in the rider-seat-vehicle system. These nonlinearities become increasingly important for ride quality estimation when the road roughness increases and when the vehicle suspension is stiff, which may lead to situations where contact between the seat and the rider is lost or the seat bottoms out.

Advances in Vehicle Suspension Design and Control

The part of a vehicle that has the strongest impact on how the vehicle interacts with the road is the suspension. Vehicle suspension characteristics are crucial for ride quality, handling, and dynamic tire forces. Traditionally, suspension designers have relied on experience, intuition, and subjective measures of a vehicle's ride and handling performance. This was primarily because of the complexity of the vehicle design and due to the lack of adequate analytical or numerical models of vehicle dynamics. In their paper, Alstead and Whitehead outline some of the objective methods developed and used by the Motor Industry Research Association in England in evaluating vehicle ride and handling performance. The authors suggest, however, that in spite of an increase in the use of objective techniques, subjective techniques will continue to play an important part in the development of new suspension designs.

Noise Emission Due to Vehicle-Tire-Road Interaction

The level of noise generated by a vehicle must be considered in two categories—exterior and interior to the vehicle. Concerns about the environmental effects of exterior vehicle noise have been growing rapidly, especially in densely populated areas. These concerns lead to legislation reducing the acceptable level of exterior noise or creating tax advantages to the manufacturers of low-noise vehicles. The implementation of the various legislative actions requires accurate and reliable noise testing procedures, which is the topic of the paper by Wagner. This paper presents the results of several studies conducted by Volkswagen in an effort to develop vehicle noise testing methods. The effects of several test variables such as road surface, type of tire, tire inflation pressure, and temperature are examined. If these variables are not controlled sufficiently, the measurements of exterior noise may vary by 3 dB or more, which constitutes a very significant error. Another very important result reported by Wagner is that, contrary to widespread opinions, tires with good traction characteristics don't necessarily have to be noisy.

The second paper in this section, authored by Voutyras and Thomson, focuses on vehicle interior noise. The primary objectives of the research reported in the paper were to investigate the effects of different road surfaces on vehicle interior noise and to develop a method that would allow for predicting the level of noise generated on different road surfaces based on vehicle noise measured on a single surface. The method, called the road surface weighting functions method, produces results that have been found to be in very good agreement with experimental data.

Fuel Efficiency and Rolling Resistance

Rolling resistance is generally considered to be a characteristic of a tire. However, from a broader perspective, rolling resistance and vehicle fuel consumption depend on characteristics of both vehicle tires and the road surface. In their paper, Gyenes and Mitchell review the results of experimental measurements of the rolling resistance and fuel consumption of cars and trucks using different types of tires and traveling on different road surfaces. Road surface macrotexture and roughness can each increase the fuel consumption of cars by 5% and trucks by 10%. On unpaved roads, this effect is further magnified by 15 to 20%. It is also stated that rolling resistance and thus fuel consumption of trucks can be reduced by the use of higher inflation pressure and wide single tires in place of dual tires. However, increased tire inflation pressure as well as replacing dual tires with wide single tires causes greater pavement wear.

In the two other papers in this section, the authors discuss the effects of the road surface characteristics, roughness and texture, on the rolling resistance of typical passenger car/tire combinations. In his paper, Delanne presents the results of a very comprehensive study conducted at the Laboratoire Central des Ponts et Chaussées in France involving tests performed in the laboratory, on a test track, and on in-service roads. The results are in good agreement with the results reported by Gyenes and Mitchell earlier in this section. The important question raised in this paper is how the low rolling resistance requirements relate to other vehicle and road characteristics such as traction and noise. The author states that road surfaces that are beneficial for fuel consumption can be detrimental to other road qualities. The paper by Cenek reports on a similar study conducted in New Zealand. It describes the development of the test method for the on-road determination of rolling resistance and the results of application of this method on a variety of roads having widely differing surface texture characteristics.

The papers published in this volume should provide the reader with the latest information and the direction for future research in the area of vehicle-road interaction. I would like to acknowledge sincerely the efforts of the authors, reviewers, ASTM personnel, and the conference organizing committee. Claude Lamure of INRETS, France, served as the conference co-chairman and the following served as members of the organizing committee: Alexander A. Alexandridis, R. B. J. Hoogvelt, Bürckhard Horn, Byron N. Lord, Mark A. Poelman, Ulf Sandberg, Elson B. Spangler, Margaret M. Sullivan, and A. Roger Williams. In addition, J. J. Henry, Charles F. Scheffey, Frank W. Schmidt, and James C. Wambold were the "ex officio" members of the committee. The support of the conference by the Federal Highway Administration is also gratefully acknowledged.

Bohdan T. Kulakowski
The Pennsylvania State University,
Pennsylvania Transportation Institute,
University Park, PA 16802.
Conference Chairman and Editor

Modeling and Simulation of Vehicle Dynamics and Vehicle-Road Dynamic Interaction

Chris H. Verheul,[1] *G. Batstra,*[2] *and S. T. H. Jansen*[1]

Simulation and Analysis of Trucks Using the Modeling and Simulation Program BAMMS

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ABSTRACT: A description is given of a general purpose, open-structured simulation tool based on the bond graph method. The method and capacities of the program are discussed. Research performed with the help of the program are discussed. Models are made of a race truck in order to study and optimize the road-handling behavior of the vehicle. The final part of the paper discusses models made of truck trailer combinations. The purpose of these simulations is to study parameter variations with respect to the stability of these vehicles. The general intention of the paper is to give an impression of the modeling and analysis approach used when working with BAMMS.

KEY WORDS: dynamic simulations, bond graphs, vehicle dynamics, handling, and stability

This paper discusses methods and features of a simulation program developed in a cooperative effort at TNO in Delft and at the Department of Mechanical Engineering of the Delft University of Technology. Two examples of research illustrate use of the program. The two topics are: the optimization process of a race truck and parameter variations in truck trailer models to study their impact on vehicle stability.

In this paper, presentation of research results is a secondary target. The main purpose of the paper is to demonstrate the advantages of a simulation program with an open-structured user interface and the possibility for on-the-fly creation of modeling and analysis tools dedicated to a certain research.

The BAMMS Simulation Program

The acronym BAMMS stands for **B**ondgraph-based **A**lgorithm for **M**odeling **M**ultibody **S**ystems. The purpose of the program is to offer a flexible, adjustable, and user-extendable software tool for development and analysis of continuous simulation models. The BAMMS program can be used to model discrete systems also, but was originally intended to model and analyze physical systems whose behavior can be described by differential and algebraic equations.

[1] Research engineer, TNO Road-Vehicles Research Institute in Delft, Schoemakerstraat 97, PO Box 6033, The Netherlands.

[2] Graduate student, Department of Mechanical Engineering, Delft University of Technology.

History of BAMMS' Development

The development of the BAMMS program started in 1985 as part of diploma work at the Delft University of Technology. The goal of the research was to obtain an advanced three-dimensional model of a passenger car. The model should be detailed enough to study the "torque steer" phenomenon. Much experience was available in the department on using the bond graph method in modeling and simulation studies [*1*,*2*]. At this point, it was decided to develop a program that introduces the advantages of the bond graph method in a multibody simulation program. Successive versions of BAMMS were used in a number of related vehicle studies and applications. The program started as a model generator for the simulation programs TUTSIM and ACSL. In 1987, in a Ph.D. study by the first author, the simulation environment of BAMMS was developed to include the possibility of on-line wire frame animations. In 1991, the Delft University of Technology and the Institute of Road-Vehicles of TNO in Delft decided to cooperate in the development of the BAMMS program. In past years, a number of full vehicle models made with BAMMS have been successfully validated by measurement data both in steady-state and transient situations.

Using Bond Graphs

The BAMMS software is separated in the modeling program and in simulation programs. In the modeling program, users create models by defining and connecting equations from predefined submodels. These submodels (macros) are stored as ASCII data in user-definable macro files. In the present version of the program, models and analysis runs are defined in a command-driven dialogue. In future versions, direct graphical input of bond graph data will be available.

Equations in the submodels are derived from bond graphs. Basically, the bond graph method defines the relations in a system by means of a graphical representation of the power flow in the system. The physical relations of the system are represented as components connected by power bonds. A limited number of standard components define power transformations and storage or dissipation of energy. Two types of summation blocks are defined in the bond graph syntax; the "one" (1) junction represents a summation of effort variables. In the mechanical domain these are forces and moments. At the same time, only one flow is defined at such a one junction. The bond graph "zero" (0) junction is a summation point of flow variables: linear and angular velocities. Similarly, at a zero junction, an effort variable is transmitted to all bonds connected to the junction. The bond graph relations in BAMMS macros are already made causal. An integrative calculation sequence has been maintained as much as possible to prevent numerical problems.

Some advantages of using bond graphs are:

1. The bond graph syntax is not limited to one physical domain; it can be used to define models in several domains. In the mechanical domain, the effort variables are represented by the forces and torques in the system. The flow variables are represented by the velocities and angular velocities in the system.
2. The bond graph method presents a logical graphical schematization of the system modeled. It offers insight in the relations existing in the system and can be adjusted and expanded very easily.
3. The method can be used both to model scalar relations and vector relations. Multibonds are defined in the syntax to model vector bonds with a variable dimension.

Although it is helpful, knowledge of the bond graph method is not required when using BAMMS.

The BAMMS programs consist of a fixed number of commands and a variable number of macros. Commands are available to perform a number of elementary actions in the model composition and in the analysis phase of the program. Macros are essentially user defined and are stored as ASCII data in separate macro files. An on-line macro interpreter is included in the BAMMS programs, which gives users the opportunity to develop and test new macros while running the program. Once a new macro has been tested and stored in one of the macro libraries, its user interface is fully identical to that of existing "standard" macros or commands.

Program Features

A number of features are implemented in BAMMS:

User-Definable Block Operators—All equations in a model are stored as blocks in an overall block diagram table. Block operators define what action must be performed to produce output variables. Output variables can be scalars, vectors, or matrices. All operators are user defined and can connect (commercially available) Fortran subroutine libraries as new program elements. Syntax checks will be performed automatically when new block operators are used in model equations.

Interactive and Batch Mode—All programs can be used both interactively and in batch. A graphical representation of the model geometry is directly generated. This offers a frame for rapid model prototyping and fast model debugging. In both program phases, all commands and macros are echoed to the model description file.

Minimized Pre- and Post Processing—The BAMMS program is an integrated set of Fortran 77 subroutines with a minimum of pre- and post processors required. Implementations of the program have been made on Unix Workstations, on MSDOS machines, and on VAX and Cray hardware platforms.

The Modeling Phase

In the modeling phase of the program, all model equations are generated. The program flow of both the modeling and the simulation phase is visualized in Fig. 1. The figure demonstrates the main program, an extendable amount of macros, and possible program input and output.

In the final stage of the modeling phase, model equations are checked, compressed, optimized, and written out as a Fortran 77 file. This file is compiled and linked to the BAMMS program libraries to produce a stand-alone simulation program.

Mechanical Macros Available in BAMMS

BAMMS contains a library of macros defining equations for models in the mechanical domain. The models are defined in a Cartesian space. Each (rigid) body introduces six degrees of freedom. The three components of the angular velocity are observed in the local body fixed frame. The three components of the linear velocity of the center of gravity of the body are considered with respect to the global inertial frame. Experience has shown that this is the most effective choice of motion variables.

Orientation transformations are performed by using direction cosines. For definition of the cosines of frames, the user can select Tayt-Bryant angles or Euler parameters.

Kinematical constraints can be set up by using Lagrangian multipliers [*3,4*]. The equations connected with constraint elements contain the necessary information for a symbolical generation of the constraint Jacobean matrix. In the simulation program, the required constraint forces

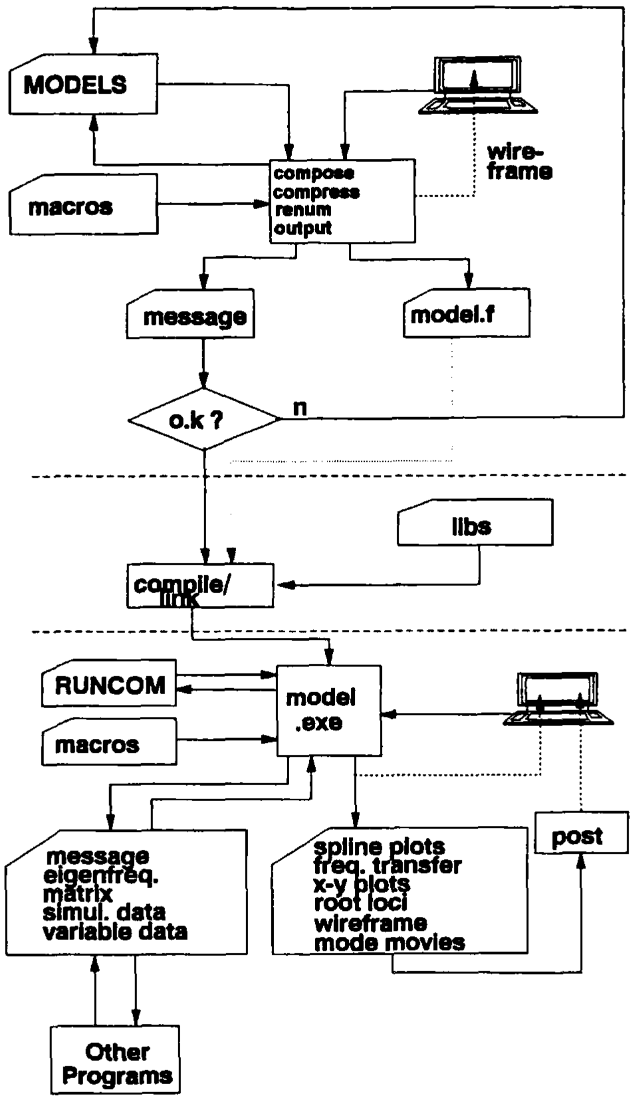

FIG. 1—*Flowchart of a BAMMS modeling and simulation run.*

are represented by Lagrangian multipliers and are solved by using Wittenburg's method. Possible numerical errors are corrected by using the Baumgarte stabilization method. The advantage of the method is that all bodies are uncoupled, meaning that the rank of the biggest inertia matrix is three. Thus, the dimension of the largest matrix to be solved in the system is equal to the number of constraints.

Mechanical macros are separated in:

Flow-producing Macros—This group contains body macros, a gyrostat macro, and the external flow source.

Transformation Macros—Defining the algebraic relationships between flows and efforts of different points in a body or mechanism and the transformation from one frame of axes to another.

Effort-producing Macros—These macros define massless connections between flow-producing macros. Macros are available to model point, line, and beam connections. To these macros, the actual effort-producing elements are attached, such as spring-dampers, relaxation spring-dampers, external effort sources, and kinematic constraints. Some other examples of effort-producing macros are the wheel macro based on the so-called "magic formulae" equations and a macro of an engine crankshaft with differential.

Simulation Program Features

Figure 1 also demonstrates that communication to external programs is possible by means of ASCII input and output data files. The format in which data is written to these files can be adjusted while running the program. This feature can be used to export BAMMS simulation data to (graphical) post processing programs. Importing numerical data from measurements and/or other software programs is also supported by this feature. Once compiled and linked, a BAMMS simulation model can be used in a flexible way. All parameters and initial values of integration blocks can be adjusted while running the simulation program.

In the simulation program, a range of commands and macros is available to perform both time domain analysis and frequency domain analysis. Time domain simulations can be performed with a selection of integration methods [*5,6*]. A number of available simulation options will be discussed in the case studies treated in the remaining part of the paper.

Analysis and Optimization of a Race Truck

Introduction

A study has been carried out for a Dutch trucking company to optimize the road-handling behavior of a Scania 143m. This truck has been used in races for a number of years and has undergone a number of modifications to improve its road holding and handling behavior. Together with students of the Delft University of Technology, the relevant parameters of the truck have been assessed, and a number of two-dimensional models have been established to analyze the behavior of the vehicle. The purpose of this research was to obtain optimum values of the roll stiffnesses and damping of the truck wheel suspensions with respect to the handling of the vehicle.

Next, more complex models have been established with BAMMS in order to obtain more accurate models of a high-powered road vehicle with a relatively flexible chassis. Models of different levels of complexity are described and compared below. A number of different methods are discussed that were used to obtain information about the influence of certain parameter variations on the vehicle's handling and stability.

Simulations were performed with two different models, a complex model and a simplified model. A short description of both models follows.

The Complex Model—The complex truck model consists of a relatively light flexible chassis frame that carries a rigid body. The body mass includes the engine and the cabin of the truck. A number of joints are defined between chassis and body. The rear of the body is connected to the chassis frame by means of a massless beam element. The chassis frame consists of two rigid bodies in the longitudinal direction of the vehicle. By means of massless flexible beams,