AUTOMOBILE COLLISION RECONSTRUCTION: A LITERATURE SURVEY

BARRY D. OLSON
CRAIG C. SMITH

RESEARCH REPORT 63

FEBRUARY 1979

TEXAS OFFICE OF TRAFFIC SAFETY

COUNCIL FOR ADVANCED TRANSPORTATION STUDIES
The University of Texas at Austin

RESEARCH REPORTS PUBLISHED BY THE COUNCIL FOR ADVANCED TRANSPORTATION STUDIES

1 *An Integrated Methodology for Estimating Demand for Essential Services with an Application to Hospital Care.* Ronald Briggs, Wayne T. Enders, James A. Fitzsimmons, and Paul Jenson, April 1975 (DOT-TST-75-81).

2 *Transportation Impact Studies: A Review with Emphasis on Rural Areas.* Lidvard Skorpa, Richard Dodge, C. Michael Walton, and John Huddleston,October 1974 (DOT-TST-75-59).

4 *Inventory of Freight Transportation in the Southwest/Part I: Major Users of Transportation in the Dallas-Fort Worth Area.* Eugene Robinson, December 1973 (DOT-TST-75-29).

5 *Inventory of Freight Transportation in the Southwest/Part II: Motor Common Carrier Service in the Dallas-Fort Worth Area.* J. Bryan Adair and James S. Wilson, December 1973 (DOT-TST-75-30).

6 *Inventory of Freight Transportation in the Southwest/Part III: Air Freight Service in the Dallas-Fort Worth Area.* J. Bryan Adair, June 1974 (DOT-TST-75-31).

7 *Political Decision Processes, Transportation Investment and Changes in Urban Land Use: A Selective Bibliography with Particular Reference to Airports and Highways.* William D. Chipman, Harry P. Wolfe, and Pat Burnett, March 1974 (DOT-TST-75-28).

9 *Dissemination of Information to Increase Use of Austin Mass Transit: A Preliminary Study.* Gene Burd, October 1973.

10 *The University of Texas at Austin: A Campus Transportation Survey.* Sandra Rosenbloom, Jane Sentilles Greig, and Lawrence Sullivan Ross, August 1973.

11 *Carpool and Bus Matching Programs for The University of Texas at Austin.* Sandra Rosenbloom and Nancy J. Shelton, September 1974.

12 *A Pavement Design and Management System for Forest Service Roads–A Conceptual Study.* Final Report—Phase I. Thomas G. McGarragh and W. R. Hudson, July 1974.

13 *Measurement of Roadway Roughness and Automobile Ride Acceleration Spectra.* Anthony J. Healey and R. O. Stearman, July 1974 (DOT-TST-75-140).

14 *Dynamic Modelling for Automobile Acceleration Response and Ride Quality over Rough Roadways.* Anthony J. Healey, Craig C. Smith, Ronald O. Stearman, and Edward Nathman, December 1974 (DOT-TST-75-141).

15 *Survey of Ground Transportation Patterns at the Dallas/Fort Worth Regional Airport,Part I: Description of Study.* William J. Dunlay, Jr., Thomas G. Caffery, Lyndon Henry, and Douglas W.Wiersig, August 1975 (DOT-TST-76-78).

16 *The Prediction of Passenger Riding Comfort from Acceleration Data.* Craig C. Smith, David Y. McGehee, and Anthony J. Healey, March 1976.

17 *The Transportation Problems of the Mentally Retarded.* Shane Davies and John W. Carley, December 1974.

18 *Transportation-Related Constructs of Activity Spaces of Small Town Residents.* Pat Burnett, John Betak, David Chang, Wayne Enders, and Jose Montemayor, December 1974 (DOT-TST-75-135).

19 *The Marketing of Public Transportation: Method and Application.* Mark Alpert and Shane Davies, January 1975 (DOT-TST-75-142).

20 *The Problems of Implementing a 911 Emergency Telephone Number System in a Rural Region.* Ronald T. Matthews, February 1975.

23 *Forecast of Truckload Freight of Class I Motor Carriers of Property in the Southwestern Region to 1990.* Mary Lee Gorse, March 1975 (DOT-TST-75-138).

24 *Forecast of Revenue Freight Carried by Rail in Texas to 1990.* David L. Williams, April 1975 (DOT-TST-75-139).

28 *Pupil Transportation in Texas.* Ronald Briggs, Kelly Hamby, and David Venhuizen, July 1975.

30 *Passenger Response to Random Vibration in Transportation Vehicles–Literature Review.* A. J. Healey, June 1975 (DOT-TST-75-143).

35 *Perceived Environmental Utility Under Alternative Transportation Systems: A Framework for Analysis.* Pat Burnett, March 1976.

36 *Monitoring the Effects of the Dallas/Fort Worth Regional Airport,* Volume I: *Ground Transportation Impacts.* William J. Dunlay, Jr., Lyndon Henry, Thomas G. Caffery, Douglas W. Wiersig, and Waldo A. Zambrano, December 1976.

37 *Monitoring the Effects of the Dallas/Fort Worth Regional Airport,* Volume II: *Land Use and Travel Behavior.* Pat Burnett, David Chang, Carl Gregory, Arthur Friedman, Jose Montemayor, and Donna Prestwood, July 1976.

38 *The Influence on Rural Communities of Interurban Transportation Systems,* Volume II: *Transportation and Community Development: A Manual for Small Communities.* C. Michael Walton, John Huddleston, Richard Dodge, Charles Heimsath, Ron Linehan, and John Betak, August 1977.

39 *An Evaluation of Promotional Tactics and Utility Measurement Methods for Public Transportation Systems.* Mark Alpert, Linda Golden, John Betak, James Story, and C. Shane Davies, March 1977.

40 *A Survey of Longitudinal Acceleration Comfort Studies in Ground Transportation Vehicles.* L. L. Hoberock, July 1976.

41 *A Lateral Steering Dynamics Model for the Dallas/Fort Worth AIRTRANS.* Craig C. Smith and Steven Tsao, December 1976.

42 *Guideway Sidewall Roughness and Guidewheel Spring Compressions of the Dallas/Fort Worth AIRTRANS.* William R. Murray and Craig C. Smith, August 1976.

43 *A Pavement Design and Management System for Forest Service Roads–A Working Model.* Final Report—Phase II. Freddy L. Roberts, B. Frank McCullough, Hugh J. Williamson, and William R. Wallin, February 1977.

44 *A Tandem-Queue Algorithm for Evaluating Overall Airport Capacity.* Chang-Ho Park and William J. Dunlay, Jr., February 1977.

45 *Characteristics of Local Passenger Transportation Providers in Texas.* Ronald Briggs, January 1977.

46 *The Influence on Rural Communities of Interurban Transportation Systems,* Volume I: *The Influence on Rural Communities of Interurban Transportation Systems.* C.Michael Walton, Richard Dodge, John Huddleston, John Betak, Ron Linehan, and Charles Heimsath, August 1977.

47 *Effects of Visual Distraction on Reaction Time in a Simulated Traffic Environment.* C. Josh Holahan, March 1977.

48 *Personality Factors in Accident Causation.* Deborah Valentine, Martha Williams, and Robert K. Young, March 1977.

49 *Alcohol and Accidents.* Robert K. Young, Deborah Valentine, and Martha S. Williams, March 1977.

50 *Alcohol Countermeasures.* Gary D. Hales, Martha S. Williams, and Robert K. Young, July 1977.

51 *Drugs and Their Effect on Driving Performance.* Deborah Valentine, Martha S. Williams, and Robert K. Young, May 1977.

52 *Seat Belts: Safety Ignored.* Gary D. Hales, Robert K. Young, and Martha S. Williams, June 1978.

53 *Age-Related Factors in Driving Safety.* Deborah Valentine, Martha Williams, and Robert K. Young, February 1978.

54 *Relationship Between Roadside Signs and Traffic Accidents: A Field Investigation.* Charles J. Holahan, November 1977.

55 *Demographic Variables and Accidents.* Deborah Valentine, Martha Williams, and Robert K. Young, January 1978.

56 *Feasibility of Multidisciplinary Accident Investigation in Texas.* Hal L. Fitzpatrick, Craig C. Smith, and Walter S. Reed, September 1977.

57 *Modeling the Airport Terminal Building for Capacity Evaluation Under Level-of-Service Criteria.* Nicolau D. Fares Gualda and B. F. McCullough, forthcoming 1979.

58 *An Analysis of Passenger Processing Characteristics in Airport Terminal Buildings.* Tommy Ray Chmores and B. F. McCullough, forthcoming 1979.

59 *A User's Manual for the ACAP Model for Airport Terminal Building Capacity Analysis.* Edward V. Chambers III, B. F. McCullough, and Randy B. Machemehl, forthcoming 1979.

60 *A Pavement Design and Management System for Forest Service Roads–Implementation.* Final Report—Phase III. B. Frank McCullough and David R. Luhr, January 1979.

61 *Multidisciplinary Accident Investigation.* Deborah Valentine, Gary D. Hales, Martha S. Williams, and Robert K.Young, October 1978.

62 *Psychological Analysis of Degree of Safety in Traffic Environment Design.* Charles J. Holahan, February 1979.

63 *Automobile Collision Reconstruction: A Literature Survey.* Barry D. Olson and Craig C. Smith, forthcoming 1979.

64 *An Evaluation of the Utilization of Psychological Knowledge Concerning Potential Roadside Distractors.* Charles J. Holahan, forthcoming 1979.

AUTOMOBILE COLLISION RECONSTRUCTION: A LITERATURE SURVEY

Barry D. Olson
Craig C. Smith

Research Report 63

February 1979

Prepared by

Council for Advanced Transportation Studies
The University of Texas at Austin
Austin, Texas 78712

For

Texas Office of Traffic Safety
State Department of Highways and Public Transportation
Austin, Texas

Technical Report Documentation Page

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

AUTOMOBILE COLLISION RECONSTRUCTION:
A LITERATURE SURVEY

5. Report Date

February 1979

6. Performing Organization Code

7. Author(s)

Barry D. Olson and Craig C. Smith

8. Performing Organization Report No.

RR 63

9. Performing Organization Name and Address

Council for Advanced Transportation Studies
The University of Texas at Austin
Austin, Texas 78712

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

(77) 72-00-02 B

12. Sponsoring Agency Name and Address

Texas Office of Traffic Safety
State Department of Highways and Public
Transportation Austin, Texas

13. Type of Report and Period Covered

Research Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A great number of papers have been written dealing with the characteristics of automobile collisions. In this report, the principal research methods which are used are reviewed and the major papers dealing with each method are surveyed. Computer techniques which have been developed within the past few years are reviewed, and their utility and limitations are discussed. A modular approach, in which individual computer modules are used interactively by an investigator to reconstruct an accident in separate phases, is suggested.

17. Key Words

Motor Vehicle Accidents, Traffic Safety, Accident Reconstruction, Automobile Accident Simulation, Computer Reconstruction of Automobile Collisions.

18. Distribution Statement

This document is available through the Council for Advanced Transportation Studies, The University of Texas as Austin, Austin, Texas 78712.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	26	

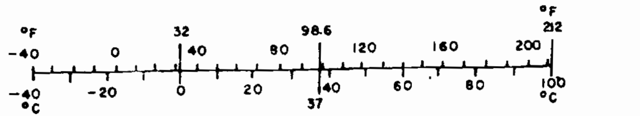
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

I. INTRODUCTION

Losses suffered by the American public from automobile accidents have been a growing problem for the last fifty years. To take effective action to reduce such losses, traffic safety officials need good information about these accidents and their causes. Automobile accident reconstruction can potentially provide reliable information which can be useful in the administration of justice for individual accident cases and for effecting highway legislation or automobile/highway design decisions when information from a variety of accidents is taken together.

A great number of papers dealing with automobile collisions have appeared in the literature. It is the purpose of this report to review the primary reconstruction techniques described in the literature and to review the principal papers associated with the methods.

II. RECONSTRUCTION METHODS

Because of the great variability in type and nature of automobile collisions, the methods of reconstruction also vary. One approach to the categorization of these methods is according to the physical laws or mechanical principles upon which they are based. The two basic principles used are the principle of impulse and momentum and the principle of work and energy. For any particular accident or phase of an accident, the principles which are most appropriately applied depend upon what is best known about the forces acting on each vehicle through each accident phase. Because some principles are typically more appropriate during one phase than another, the principles are discussed relative to impact and trajectory phases.

More detailed examination of any phase of an accident is possible using a digital computer simulation, and simulation techniques have therefore been developed by various sources during the past few years. The most prominent simulation techniques are therefore described and evaluated, including some discussion of the computer programs SMAC and CRASH, which were developed under contract to the National Highway Traffic Safety Administration. In general, there is a lack of computational efficiency in these programs because of the program generality required to simulate a large variety of accidents.

III. PRINCIPAL CONCLUSIONS AND RECOMMENDATIONS

A variety of automobile accident reconstruction methods are presently available. Because of the variability among accidents, the selection of the reconstruction principles to be applied in analyzing a given accident should be on the basis of the data available for that accident. It is suggested that, to facilitate this, a computer reconstruction system should be developed in modular form. Individual program modules could then be selected based upon the data available, and thus the reconstruction program could be tailored to the specific reconstruction problem needs.

TABLE OF CONTENTS

AUTOMOBILE COLLISION RECONSTRUCTION:
A LITERATURE SURVEY

AUTOMOBILE COLLISION RECONSTRUCTION : A LITERATURE SURVEY

I. INTRODUCTION

A great number of papers dealing with the characteristics of automobile collisions have appeared in the literature. The overall motivation for pursuing the study of automobile collisions is to improve the safety of automobile travel through a better understanding of the predominant characteristics which lead to accidents and influence injury severity. Quantification of conditions of accidents and of vehicle and occupant behavior has led to many improvements in the design of vehicles and roadways, as well as being an aid to our legal system in administering justice. Simulation of vehicle collisions has played an important role in this progress. Yet, substantial potential for further improvement exists.

A discussion of the factors affecting occupant injury in automobile collisions is presented by Marquardt.[1] Marquardt has organized these factors into groups of vehicle-related factors (those relating to the collision external to the occupant compartment) and occupant-related factors (those which relate to occupant compartment interactions). The analysis presented shows that the actual injury incurred is determined by occupant-related factors for a given Peak Contact Velocity (PCV). Peak Contact Velocity is defined as the maximum relative velocity with which the occupant will contact the vehicle interior. The PCV is essentially the velocity change of the vehicle during the crushing phase, when the vehicles are brought from their original velocities to a common velocity in the forward phase of impact. Consequently, the determination of velocity changes in vehicle accidents is an important step in quantifying injury severity potential. The actual injury is a function of many occupant-related factors, and Marquardt has concluded that a statistically valid sample of the random occupant variables is necessary for drawing conclusions about the correlation of injuries to accident conditions.

---

[1] J.F. Marquardt, "Vehicle and Occupant Factors that Determine Occupant Injury," SAE paper 740303 (1974).

Although accidents staged with test dummies present a method for generating statistical data, a much larger number of accidents exists in the field. With the development of simulation techniques applicable to the reconstruction of field accidents, the first step towards tapping this data has been made. The National Highway Traffic Safety Administration is now sponsoring a National Crash Severity Study to obtain the first statistical data using a computer simulation program to reconstruct a large number of accidents across the nation.

The purpose of this paper is to present a survey of the current literature available with respect to the development of accident simulation techniques. Before dynamic principles and simulation techniques are discussed, the reader is referred to J.F. Wilson's article "Two-Vehicle Collision Reconstruction: A Rational Computer-Aided Approach " for insight into the reconstruction problem.[2] For the two-vehicle collision model, Wilson presents one possible set of system parameters (40 in this particular case) which could be used to define the impact and post-impact trajectory phases of an accident. Depending on the particular accident, the available evidence (e.g., tracking data and post-collision inspections), and the mechanical principles used to simulate or reconstruct the accident, the set of system parameters may be altered. However, Wilson's classification of the system parameters into subsets (most certain, less certain, least certain, and definite unknowns) defines a logical process for evaluating parameters for any given accident. As indicated, the common goal of simulations is generally to determine initial velocities and velocity changes, whether the motivation is an interest in occupant movement and injury potential studies, legal investigations, or other.

---

[2] J.F. Wilson, "Two-Vehicle Collision Reconstruction: A Rational Computer-Aided Approach," Vehicle System Dynamics 2 (1973).

II. MECHANICAL PRINCIPLES

The reconstruction of vehicle collisions by using the dynamic principles of rigid bodies is certainly nothing new. With the introduction of the digital computer the capability to substantially increase the complexity of the reconstruction existed and it has been exercised. However, regardless of the complexity introduced, a basic understanding of the principles of impulse-momentum and conservation of mechanical energy with applicable assumptions is needed. Although there are different approaches for analyzing a collision, in general, vehicle collision reconstruction is separated into distinct phases of impact and pre- and post-collision trajectory. Consequently, the principles as applied to the individual phases will be discussed separately. Note should be made that, with the division of the analysis into separate phases (events) as presented here, the impact phase is modeled assuming that tire forces are negligible during that phase. Although this assumption is reasonable for most collisions, as noted by Grime and Jones and by McHenry,[3] McHenry indicates that significant errors have resulted for moderate-speed intersection collisions in which multiple contacts occur.

A. Impact Phase: Principle of Impulse and Momentum

Most introductory dynamics texts present a discussion of the application of the principle of impulse-momentum (conservation of momentum) to the basic impact problem. Beer and Johnston present introductory discussions for both central and eccentric impact.[4] A more complete yet fundamental treatment of the principle of impulse-momentum with specific reference to vehicle collision impact can be found in Reizes.[5] More detailed presentations of the principle applied to the impact problem can be found in

---

[3] G. Grime and I.S. Jones, "Car Collisions--The Movement of Cars and Their Occupants in Accidents," Proceedings of Institute of Mechanical Engineering 184 (1969-70); R.R. McHenry, "Computer Program for Reconstruction of Highway Accidents," SAE paper 730980 (1973).

[4] F.P. Beer and E.R. Johnston, Jr., Vector Mechanics for Engineers: Dynamics 2nd ed. (New York: McGraw-Hill, 1972).

[5] H. Reizes, The Mechanics of Vehicle Collisions (Springfield, IL: Charles C. Thomas, 1973).

Emori and in Goldsmith.[6]

Several assumptions are made in the application of the principles of rigid bodies to vehicle collisions. In traffic accidents the bodies (vehicles) undergo elastic and plastic deformations. Although the centers of gravity of the bodies are affected, the locations of the centers of gravity do not change radically during the impact phase and, therefore, are assumed to be constant. The mass moments of inertia of the vehicles are also assumed to be constant during and following deformation. Due to the substantial crushing involved in severe collisions, portions of the body structure (e.g., the occupant compartment) take an appreciable, though still short, time to reach a common velocity. Consequently, portions of the body structure or mass may undergo a change in velocity before the rest of the vehicle. This effect is not modeled in detail and all of the mass of the vehicle is assumed to have the same velocity at all times. In current simulations only two-dimensional vehicle motion has been included. Although pitching and rolling are present in essentially "planar" accidents, their effects are typically small and are, therefore, neglected. The influence of the preceding assumptions are considered by Grime and Jones.[7]

The impact phase of a collision can be further broken down into periods or subphases. Immediately following a collision, the relative velocities of two masses will tend to be equalized as the masses continue along their initial trajectories interacting by impulsive forces. Once a common velocity is reached, the forward impact, or period of deformation, of the collision terminates. At this instant, reaction forces acting to separate the masses are present if at least one of the masses is elastic to some degree. This period of the impact is commonly called the period of restitution, or rebound. It ends when the reaction force reduces to zero at vehicle separation.

---

[6] R.I. Emori, "Vehicle Mechanics of Intersection Collision Impact," SAE paper 700177 (January 1970); W. Goldsmith, Impact (London: Edward Arnold, 1960).

[7] Grime and Jones, "Car Collisions."

The ratio of the forces acting during the period of restitution to those during the period of deformation is called the coefficient of restitution. This ratio may also be viewed as that of the momentum transfer at rebound to the momentum transfer during crush. The coefficient of restitution varies between zero, for a perfectly plastic collision, and one, for a perfectly elastic collision. The principle of conservation of momentum is valid regardless of the value of the coefficient of restitution. In general, total mechanical energy is not conserved in impact problems except where the impact is perfectly elastic. Therefore, the coefficient of restitution serves as a measure of energy loss as previously noted.

In application to vehicle collisions, the coefficient of restitution tends to be small, depicting the almost inelastic behavior of crushing automobiles. The coefficient of restitution is typically on the order of 0.05 to 0.1 for symmetric head-on collisions of two automobiles.[8] Consequently, it is common to assume perfectly plastic collisions which result in a common velocity after impact. Confirmation of the assumption of small coefficients of restitution is given by Marquardt, who has determined that a change of the coefficient from 0.0 to 0.1 would change the amount of energy absorbed by only one percent.[9]

Given ample evidence, the assumption of an a priori coefficient of restitution is not required, and it is possible to calculate the coefficient. This calculation also provides a subjective check on the accuracy of the interpretation of the available evidence. The validity of the assumption of a perfectly plastic collision may be subjectively evaluated by considering the final relative positions of the vehicles involved.[10] Caution must be taken in considering the final distance between two vehicles as representative of the degree of elastic behavior because many variables which enter into the post-trajectory phase of a collision affect final rest positions.

---

[8] Ibid.

[9] Marquardt, "Vehicle and Occupant Factors."

[10] R.M. Brach, "An Impact Moment Coefficient for Vehicle Collision Analysis," SAE paper 770014 (February 1977).

Another treatment of the impact phase of a vehicle collision concentrating on an approach using the equations of impulse and momentum is presented by Brach.[11] Due to the inability to exactly locate the point of application of the resultant force impulses in vehicle collisions, Brach contends that the resultant of the total surface contact forces should consist of both force and moment impulses to accurately formulate the equations of impact. For a physical interpretation, the moment can be considered to be generated by the mechanical interlocking of parts of the deforming vehicles. In including moment impulse in the formulation, an impulse moment coefficient, similar to the coefficient of restitution, is introduced, corresponding to angular velocities. The moment coefficient ranges between negative and positive one. At negative one the angular impact is elastic, at zero the vehicles have zero relative angular velocity following impact, and at positive one no moment is transmitted at impact relating to the direct central impact problem.

Brach's paper is the only known source to consider surface moment impulse in the context of vehicle collisions. Because little work has been done with this concept, it would be difficult to establish a priori values for the moment coefficient in vehicle collision analysis. When ample collision evidence is known, the moment coefficient can be treated as an unknown and the analysis accuracy can be improved. Brach presents one example in which the moment coefficient was treated as an unknown and calculated to equal 0.70. The relatively high moment coefficient value, approaching the direct central impact value, as well as the accuracy of collision analysis by others in which the moment impulse is ignored, would lead one to question the need for this approach and the additional complexity it introduces. However, the theory offers improved accuracy and additional work in this area appears warranted.

B. Impact Phase: Conservation of Mechanical Energy

Another approach to the analysis of the impact phase of vehicle collisions

---

[11] Ibid.

is to use the principle of conservation of mechanical energy. The summation of the initial kinetic energies before impact and the energy absorbed (negative) by plastic deformation during the period of deformation, for the vehicles involved, must equal the summation of the kinetic energies of the vehicles at the instant the period of restitution ends.

To use this balance of mechanical energy to reconstruct vehicle collisions, a method for determining deformation energy terms from post-collision crush profiles is needed. Wilson uses vehicle-to-vehicle crush data,[12] showing that the mean vehicle crush deformation is linearly correlated to vehicle impact speed, to calculate the plastic work.[13] An identical linear correlation based on barrier test data for frontal impact is presented by Campbell to calculate what he refers to as an Equivalent Barrier Speed (EBS) for estimation of the energy absorbed by plastic deformation.[14] Equivalent Barrier Speed is commonly defined as the speed at which equivalent vehicle damage (based on equivalent energy absorption) is produced in a fixed barrier test of the same vehicle. Campbell tabulates the coefficients of the linear equation and the standard weight at which these coefficients were determined for four classifications of vehicles. A linear force-deflection model which reproduces the barrier test linear relationship using the same coefficients is also developed. The tabulated data are valid only for frontal impact due to the limited availability of additional test data; however; the concept is valid for all types of collisions. Campbell proposes that the factors involved in a collision could be used to classify collisions into categories where EBS formulations valid for the particular categories could be used. To arrive at the additional EBS formulations, test programs supplemented by accident simulations are needed.

---

[12] R.P. Mason and D.W. Whitcomb, "The Estimation of Accident Impact Speed," Cornell Aeronautical Laboratory Report No. YB-3109-V-1 (August 1972).

[13] Wilson, "Two-Vehicle Collision Reconstruction."

[14] K.L. Campbell, "Energy Basis for Collision Severity," SAE paper 740565 (1974).

C. Trajectory Phases: Conservation of Mechanical Energy

The trajectory phases of an accident can be reconstructed on the basis of conservation of mechanical energy. Following vehicle separation at the end of the period of restitution of the impact phase, the kinetic energy levels possessed by the individual vehicles are reduced to zero by frictional work between the vehicle and roadway. Thus the summation of translational and rotational kinetic energy following impact and of the frictional work (always negative work) during the post-collision trajectory must equal zero. Brief presentations of the principle and a means of calculating the total frictional work can be found in Emori and Taui and in Wilson.[15]

McHenry presents another discussion of post-impact-trajectory analysis based on energy dissipation by frictional work between vehicle separation and rest positions.[16] Although this presentation is not a unique solution based on the theory, more detail of the development is provided. Steering is not considered in a detailed sense, and, in the initial development, a piecewise linear idealization of the linear and angular velocity time histories is assumed with abrupt changes in deceleration rates between linear and angular motion. In other words, when the vehicle slides laterally, the angular velocity is assumed constant while the linear velocity is decelerated, and the opposite is assumed when the direction of linear velocity is aligned with the longitudinal axis of the vehicle. By approximate integrations of the idealized velocity versus time plots and rigid body mechanics, approximate linear and angular deceleration times are found. Assuming the linear and angular phases of motion end at approximately the same time, equations relating the separation velocities to displacements, the friction coefficient, and vehicle geometry are derived. Although this initial development has been found to have several shortcomings, it is a fairly complicated approach and offers an alternative method for trajectory analysis. This general approach as well as a method based on integration of equations of motion will be further discussed later in this paper.

---

[15] R.I. Emori and M. Taui, "Vehicle Trajectories After Intersection Collision Impact," SAE paper 700176 (January 1970); and Wilson, "Two-Vehicle Collision Reconstruction."

[16] R.R. McHenry, "A Comparison of Results Obtained with Different Analytical Techniques for Reconstruction of Highway Accidents," SAE paper 750893 (1975).

Note that although the discussion has been focused on post-impact-trajectory analysis, the principles can as easily be applied to pre-impact trajectories in order to find initial velocities prior to braking or skidding. Typically, pre-impact-trajectory analysis is simplified because angular velocities are negligible.

III. SIMULATION TECHNIQUES

In this section a discussion of several simulation techniques combining available evidence and mechanical principles are presented. As described in the previous section, alternative methods for developing simulation techniques exist, and the techniques presented in the following discussion will reemphasize this fact. However, the simulation techniques discussed are not limited to the general approaches previously presented.

Vehicle collisions have been reconstructed for some time with hand calculations by using the dynamic principles of rigid bodies, as previously discussed. Given accident layouts with tire tracks, impact point, and rest positions, an investigator can estimate accident conditions. The velocity of each vehicle at the termination of the period of restitution can be aproximated by using conservation of mechanical energy and assuming friction factors. With further assumptions and the principle of impulse and momentum, the impact phase can be analyzed to approximate inital contact velocities. If tire tracks indicate braking or skidding before impact, conservation of mechanical energy can again be used to approximate initial velocities. By varying the assumed values in the calculations (e.g., friction coefficients), a sensitivity study can be made and for most accidents a reasonably accurate reconstruction is obtainable. Reizes reconstructs several vehicle collisions with hand calculations.[17]

Wilson outlines two individual algorithms applicable to the estimation of initial speeds and the post-impact-trajectory lengths of an accident.[18] The algorithms are not designed to be used together as modules, as the input and outputs between them are not consistent.

---

[17] Reizes, Mechanics of Vehicle Collisions.

[18] Wilson, "Two-Vehicle Collision Reconstruction."

The first algorithm has outputs of initial velocities, post-impact linear and angular velocities, and the force impulse. The algorithm is based on the conservation of mechanical energy in combination with the impulse-momentum principle. This approach is different from those discussed previously in that the force impulse is left as an unknown and the coefficient of restitution is not introduced. A numerical example of an oblique impact is used to illustrate the algorithm. Another example of a central impact is also presented; however, in this case the algorithm as previously presented was not implemented. Instead Wilson uses the conservation of mechanical energy in combination with the conservation of linear momentum where the force impulse has been eliminated as a variable. The assumption of a coefficient of restitution is not noted, although its use is implicit in the assumption of a common post-impact velocity, which is equivalent to assuming a coefficient of restitution equal to zero.

The second algorithm for trajectory estimation uses a vector equation describing the locations of the vehicles in combination with equations used in the first algorithm to arrive at admissible solutions. In this case the definite unknowns are the post-impact-trajectory lengths. Initial velocities are classified as least certain and are input with lower and upper bounds. Numerical examples for the second algorithm are not presented.

Calspan Corporation appears to have done more in the area of accident reconstruction by computer simulation than anyone else.[19] It is Calspan's CRASH computer program which is being used in the National Crash Severity Study mentioned in the introduction. The Calspan Reconstruction of Accident Speeds on the Highway (CRASH) program is actually a refinement of a routine (START) used to generate initial approximations for a much more detailed simulation program called SMAC (Simulation Model for Automobile Collisions).

---

[19] R.R. McHenry, "Development of a Computer Program to Aid the Investigation of Highway Accidents," Cornell Aeronautical Laboratory Report No. VJ-2979-V-1 (December 1971); R.R. McHenry *et al.*, "Mathematical Reconstruction of Highway Accidents," Interim Technical Report No. DOT-HS-800 801, prepared by Calspan Corp. for DOT (January 1973); McHenry, "Computer Program for Reconstruction"; McHenry, "Comparison of Results"; and R.R. McHenry and J.P. Lynch, "CRASH-2 User's Manual," Cornell Aeronautical Laboratory Report No. ZQ-5708-V-4 (September 1976).

The SMAC program is an algorithm which predicts a time history response and corresponding evidence (i.e., rest positions, damage, and tire marks and tracks) when initial approximations of the collision conditions are input. In the reconstruction of accidents, successive iterative runs are performed until an acceptable match with real accident evidence is obtained.

In general, the uniqueness of SMAC is in its generality and the extent of analytical detail. Equations based on the fundamental physical laws and empirical relationships are used to balance the applied and inertial forces and moments acting on vehicles throughout an accident. Empirical laws are introduced to treat collision and tire forces simultaneously. The analytical assumptions which are made for the collision force aspect of the impact and differ substantially from those previously discussed are outlined by McHenry:

1. the vehicles are treated as rigid bodies, each surrounded by a layer of isotropic, homogeneous material exhibiting elastic-plastic behavior;
2. the dynamic pressure in the peripheral layer increases linearly with the depth of penetration relative to the initial boundary of the deflected surface;
3. the adjustable, nonlinear coefficient of restitution varies as a function of maximum deflection.

The "friction circle" concept for introducing tire forces, which is a method of limiting tire forces to those obtainable by coulomb friction, is also outlined by McHenry.[20]

The SMAC-predicted time histories of vehicle responses during impact and spinout trajectories are generated by step-by-step integration of continuous equations of motion over the time interval of the accident. A derivation of the equations implemented in SMAC is outlined by McHenry.[21] A simpler presentation of equations of motion applicable to vehicle collisions

---

[20] McHenry, "Computer Program for Reconstruction."

[21] McHenry, "Development of a Computer Program."

is outlined in Appendix 2 of the paper by Grime and Jones.[22] Although, as McHenry shows, SMAC is obviously more complex in its treatment of collision and tire forces than the presentation in Grime and Jones, the integration of equations of motion to generate time responses should be readily apparent from either reference.

The SMAC program has been found to yield ± 5 percent accuracy in velocity estimation in certain test cases.[23] However, a sufficiently detailed definiton of the accident is required to obtain this level of accuracy and to take advantage of the benefits provided by SMAC predictions. There are numerous examples in the literature of application of SMAC.[24] The development of the CRASH program was prompted by a need to reconstruct accidents where a detailed definition of the accident was lacking. Although the range of accuracy with CRASH is decreased to about ± 12 percent, a 75 percent cost savings per run is obtained and the program inputs are less detailed. These factors provide for a broader application potential. A discussion of CRASH and comparative results from CRASH and SMAC is presented by McHenry.[25]

The CRASH program contains two methods of analyzing accident evidence. The first method is an extension of the trajectory analysis, based on energy dissipation by frictional work,[26] introduced earlier in this paper. Application of this trajectory analysis to SMAC-generated spinout trajectories revealed that shortcomings existed due to assumptions and idealizations in the original derivation. Modifications were introduced to avoid the assumption that linear and angular motion terminated simultaneously, the errors introduced in the integration of the velocity plots, and the assumptions that

---

[22] Grime and Jones, "Car Collisions."

[23] McHenry, "Comparison of Results."

[24] M.E. James, Jr., and H.E. Ross, Jr., "Improvement of Accident Simulation Model," Texas A&M Research Foundation Report No. RF-3258-1 (November 1976); McHenry, "Development of a Computer Program"; McHenry _et_ _al_., "Mathematical Reconstruction"; and McHenry, "Computer Program for Reconstruction."

[25] McHenry, "Comparison of Results."

[26] Ibid.

deceleration rates between linear and angular motions changed abruptly. Although the details of the modifications are sketchy, it is apparent that SMAC was implemented to generate empirical relationships used in the resulting equations. By combining this trajectory analysis with an impact phase analysis based on the impulse-momentum principle, the change in velocity during impact and initial impact velocities are obtained.

The second analysis method in CRASH is an extension of Campbell's damage analysis technique.[27] The linear damage analysis is based on a spring-mass-dissipator system using potential energy relationships and conservation of momentum to derive expressions for velocity changes during the impact phase as a function of the absorbed energy in crushing deformation. The absorbed energy calculation is based on Campbell's work in which gross approximations are made for the empirical coefficients for side and rear collisions. The computation of the absorbed energy is accomplished by integration of the energy equations by trapezoidal approximations where coefficients are shown in tables.

The impact phase velocity changes calculated with the two analysis methods contained in the CRASH program are comparable, although the trajectory analysis must be used in both cases to calculate initial impact velocities.

IV. CRITIQUE: APPLICATION OF COMPUTER SIMULATION

The first computer program to be used on a large scale for accident reconstruction was Calspan's SMAC program. As previously noted, the SMAC program was designed to be very general, thus allowing its application to a large spectrum of accidents, assuming sufficient detailed evidence existed. The generality, however, causes several problems. First, the program is of significant size, requiring a large computer for storage and computation. At The University of Texas at Austin, where the program has been used to reconstruct field accidents, it was advantageous to store SMAC and do computation on a CDC 6600, while input and output were handled with a PDP 11/40. Calspan used

---

[27] Campbell, "Energy Basis for Collision Severity."

a similar approach to handle the program at one time, as described by McHenry _et al_.[28] Second, it is likely that the complexity and analytical detail incorporated into the program are not required to obtain comparable accuracy for certain accidents. The second point is especially true when detailed evidence is not available. For instance, for frontal impact accidents at high speeds a simplified reconstruction using the assumption of a coefficient of restitution equal to zero is likely to be of sufficient complexity to obtain suitably accurate results.

Some of the drawbacks noted above for the SMAC program contributed to Calspan's reasoning for developing CRASH, as previously noted. The alternative methods provided with CRASH for approximating impact phase speed change make it possible for the user to select the results based on the most reliable evidence available. At the same time, comparison of results from the alternative methods provides a check on the compatibility of the various evidence items. The drawback encountered with the CRASH program is the loss in accuracy.

The accuracy loss in the CRASH trajectory analysis routine is due to the use of approximations, leading to idealized velocity versus time plots for the derivation of the energy balance equations representing the trajectory phase, instead of direct integration of equations of motion during this phase. In SMAC the equations of motion are integrated directly over the trajectory phase as well as the impact phase. Integration of the equations of motion over the impact phase introduces a number of disadvantages due to the short interval of impact time during which rapid changes take place, as the integration time steps must be very small to maintain accuracy. Additionally, SMAC requires a great deal of computational effort at each time step during the impact phase to balance the pressures acting on the vehicles across the impact interface. Therefore, the impact phase analysis used in the CRASH program, which is based on the impulse-momentum principle, is a worthwhile trade-off for simplification. However, for the trajectory phase, large time steps are

---

[28] McHenry _et al_., "Mathematical Reconstruction."

appropriate and interface pressures need not be calculated, making the trade-off to a less accurate solution, such as the CRASH program trajectory analysis, questionable.

For the damage-based approximations of the CRASH program, based on Campbell's work,[29] the main drawback, as previously noted, is the lack of experimental data for other than frontal impacts. For this reason it may be desirable to rely more heavily on other methods of approximation, such as impulse-momentum solutions. However, there are classes of accidents for which impulse-momentum methods are not applicable, (e.g., accidents at slower speeds), and a method based on damage analysis is the only attractive alternative. In this case the CRASH program damage analysis is as good as one may expect to achieve with a simplified approach and is suitable for most cases.[30]

The two algorithms developed by Wilson are similiar in nature to the CRASH program.[31] However, both of these algorithms rely on calculating the total plastic work using a linear correlation between vehicle impact speed and mean vehicle crush.[32] It is not evident in the literature that the validity of the algorithms has been substantiated, and it is extremely doubtful the results could be any more accurate than those of CRASH.

In conclusion, it appears that a number of different algorithms or modules appropriate to different classes of accidents with different types of evidence would be an attractive alternative to a general algorithm for application to a wide spectrum of accidents. By using a modular approach extended to apply to different stages of any particular accident, the complexity of the total package could be reduced while taking advantage of the specific evidence available and making appropriate simplifying assumptions. As a proposed scheme an algorithm package including a trajectory analysis based on the full integration of equations of motion and an impact analysis based on the principles of impulse and momentum could be used to reconstruct accidents with full impacts.

---

[29] Campbell, "Energy Basis for Collision Severity."

[30] McHenry, "Comparison of Results."

[31] Wilson, "Two-Vehicle Collision Reconstruction."

[32] Mason and Whitcomb, "Estimation of Accident Impact Speed."

V. SUMMARY

The common goal of vehicle accident simulations is generally to determine initial velocities and velocity changes, whether the purpose is occupant movement and injury potential studies, legal investigations, or other. To explore the alternative methods of accident simulation or reconstruction, an understanding of the application of the principles of impulse-momentum and conservation of mechanical energy with applicable assumptions is needed. Dividing the vehicle accident into separate phases of impact and pre- and post-trajectories, the basic principles and assumptions were discussed in this report as they pertain to each phase. A wide variety of potential simulation algorithms, combining different assumptions, models, and mechanical principles exist. Several algorithms developed by Wilson[33] and Calspan Corporation[34] were discussed and critiqued. It is the authors' opinion that a package of modular algorithms, including a trajectory analysis based on the integration of equations of motion and an impact analysis based on the principles of impulse and momentum, is the most advantageous approach to vehicle accident simulation. This type of algorithm package would be applicable to different phases of vehicle accidents under different circumstances (accident classifications) and is an approach that would maintain simplicity and take full advantage of applicable assumptions under the different circumstances.

---

[33] Wilson, "Two-Vehicle Collision Reconstruction."

[34] See note 19.

BIBLIOGRAPHY

Baker, S.J. "Traffic Accident Investigation Manual." Evanston, IL: The Traffic Institute, Northwestern University, 1975.

Beer, F.P., and E.R. Johnston, Jr. Vector Mechanics for Engineers: Dynamics. 2nd ed. New York: McGraw-Hill, 1972.

Bhushan, B. "Analysis of Automobile Collisions." SAE paper 750895, October 1975.

Brach, R.M. "An Impact Moment Coefficient for Vehicle Collision Analysis." SAE paper 770014, February 1977.

Campbell, K.L. "Energy Basis for Collision Severity." SAE paper 740565, 1974.

Emori, R.I. "Analytical Approach to Automobile Collisions." SAE paper 680016, January 1968.

__________. "Vehicle Mechanics of Intersection Collision Impact." SAE paper 700177, January 1970.

Emori, R.I., and D. Link. "A Model Study of Automobile Collisions." SAE paper 690070, January 1969.

Emori, R.I., and M. Taui. "Vehicle Trajectories After Intersection Collision Impact." SAE paper 700176, January 1970.

Goldsmith, W. Impact. London: Edward Arnold, 1960.

Greene, J.E. "Computer Simulation of Car-to-Car Collisions." SAE paper 770015, February 1977.

Grime, G., and I.S. Jones. "Car Collisions--The Movement of Cars and Their Occupants in Accidents." Proceedings of the Institute of Mechanical Engineers 184, 1969-70.

James, M.E., Jr., and H.E. Ross, Jr. "Improvement of Accident Simulation Model." Texas A&M Research Foundation Report No. RF-3258-1, November 1976.

Marquardt, J.F. "Vehicle and Occupant Factors that Determine Occupant Injury." SAE paper 740303, 1974.

Mason, R.P. and D.W. Whitcomb. "The Estimation of Accident Impact Speed." Cornell Aeronautical Laboratory Report No. YB-3109-V-1, August 1972.

McHenry, R.R. "Development of a Computer Program to Aid the Investigation of Highway Accidents." Cornell Aeronautical Laboratory Report No. VJ-2979-V-1, December 1971.

____________. "Computer Program for Reconstruction of Highway Accidents." SAE paper 730980, 1973.

____________. "A Comparison of Results Obtained with Different Analytical Techniques for Reconstruction of Highway Accidents." SAE paper 750893, 1975.

McHenry, R.R., and J.P. Lynch. "CRASH-2 User's Manual." Cornell Aeronautical Laboratory Report No. ZQ-5708-V-4, September 1976.

McHenry, R.R., D.J. Segal, J.P. Lynch, and P.M. Henderson III. "Mathematical Reconstruction of Highway Accidents." Interim Technical Report DOT-HS-800 801. Prepared by Calspan for DOT. January 1973.

Reizes, H. The Mechanics of Vehicle Collisions. Springfield, IL: Charles C. Thomas, 1973.

Wilson, J.F. "Two-Vehicle Collision Reconstruction: A Rational Computer-Aided Approach." Vehicle System Dynamics 2, 1973.

ABOUT THE AUTHORS

Barry D. Olson is presently a graduate student and Research Assistant at The University of Texas at Austin, where he will receive a Master of Science degree in Mechanical Engineering in May 1979. While at Texas he has been a recipient of an Alcoa Foundation Fellowship. A native of Wyoming, he received a B.S.M.E. from the University of Wyoming in May 1975. While an undergraduate at Wyoming he worked for Texas Instruments, Inc., in Dallas, Texas, in the summer of 1973 and for Eastman Kodak Company in Rochester, New York, in the summer of 1974. Following his graduation from the University of Wyoming he worked for the Trane Company in La Crosse, Wisconsin, as a Development Engineer in the Commercial Air Conditioning Division before entering Graduate School at Texas in September 1977.

Craig C. Smith, presently Assistant Professor of Mechanical Engineering at The University of Texas at Austin, holds B.S.M.E. and M.S. degrees from Brigham Young University and a Ph.D. degree from the Massachusetts Institute of Technology. He has taught courses covering a variety of topics, specializing in the areas of systems dynamics, control systems, machine design, and vibrations. He has published several papers and reports dealing with vehicle and systems dynamics.

He has been employed during summers with U.S. Steel Corporation, Bell Telephone Laboratories, and IBM Corporation and has had a variety of industrial consulting experience.

He presently serves as Chairman of the Technical Panel on System Modeling and Identification for the Dynamic Systems and Control Division of the American Society of Mechanical Engineers. He is also a member of the Society of Automotive Engineers, Sigma Xi, Phi Kappa Phi, and Tau Beta Pi and is a registered Professional Engineer in the state of Texas.

RESEARCH MEMORANDA PUBLISHED BY
THE COUNCIL FOR ADVANCED TRANSPORTATION STUDIES

1 *Human Response in the Evaluation of Modal Choice Decisions.* Shane Davies, Mark Alpert, and Ronald Hudson, April 1973.

2 *Access to Essential Services.* Ronald Briggs, Charlotte Clarke, James Fitzsimmons, and Paul Jensen, April 1973.

3 *Psychological and Physiological Responses to Stimulation.* D. W. Woolridge, A. J. Healey, and R. O. Stearman, August 1973.

4 *An Intermodal Transportation System for the Southwest: A Preliminary Proposal.* Charles P. Zlatkovich, September 1973.

5 *Passenger Travel Patterns and Mode Selection in Texas: An Evaluation.* Shane Davies, Mark Alpert, Harry Wolfe, and Rebecca Gonzalez, October 1973.

6 *Segmenting a Transportation Market by Determinant Attributes of Modal Choice.* Shane Davies and Mark Alpert, October 1973.

7 *The Interstate Rail System: A Proposal.* Charles P. Zlatkovich, December 1973.

8 *Literature Survey on Passenger and Seat Modeling for the Evaluation of Ride Quality.* Bruce Shanahan, Ronald Stearman, and Anthony Healey, November 1973.

9 *The Definition of Essential Services and the Identification of Key Problem Areas.* Ronald Briggs and James Fitzsimmons, January 1974.

10 *A Procedure for Calculating Great Circle Distances Between Geographic Locations.* J. Bryan Adair and Marilyn Turnbull, March 1974.

11 *MAPRINT: A Computer Program for Analyzing Changing Locations of Non-Residential Activities.* Graham Hunter, Richard Dodge, and C. Michael Walton, March 1974.

12 *A Method for Assessing the Impact of the Energy Crisis on Highway Accidents in Texas.* E. L. Frome and C. M. Walton, February 1975.

13 *State Regulation of Air Transportation in Texas.* Robert C. Means and Barry A. Chasnoff, April 1974.

14 *Transportation Atlas of the Southwest.* Charles P. Zlatkovich, S. Michael Dildine, Eugene Robinson, James S. Wilson, and J. Bryan Adair, June 1974.

15 *Local Governmental Decisions and Land-Use Change: An Introductory Bibliography.* William Dean Chipman, May 1974.

16 *An Analysis of the Truck Inventory and Use Survey Data for the West South Central States.* Michael Dildine, July 1974.

17 *Towards Estimating the Impact of the Dallas-Fort Worth Regional Airport on Ground Transportation Patterns.* William J. Dunlay, Jr., and Lyndon Henry, September 1974.

18 *The Attainment of Riding Comfort for a Tracked Air-Cushion Vehicle Through the Use of an Active Aerodynamic Suspension.* Bruce Gene Shanahan, Ronald O. Stearman, and Anthony J. Healey, September 1974.

19 *Legal Obstacles to the Use of Texas School Buses for Public Transportation.* Robert Means, Ronald Briggs, John E. Nelson, and Alan J. Thiemann, January 1975.

20 *Pupil Transportation: A Cost Analysis and Predictive Model.* Ronald Briggs and David Venhuizen, April 1975.

21 *Variables in Rural Plant Location: A Case Study of Sealy, Texas.* Ronald Linehan, C. Michael Walton, and Richard Dodge, February 1975.

22 *A Description of the Application of Factor Analysis to Land Use Change in Metropolitan Areas.* John Sparks, Carl Gregory, and Jose Montemayor, December 1974.

23 *A Forecast of Air Cargo Originations in Texas to 1990.* Mary Lee Metzger Gorse, November 1974.

24 *A Systems Analysis Procedure for Estimating the Capacity of an Airport: A Selected Bibliography.* Chang-Ho Park, Edward V. Chambers III, and William J. Dunlay, Jr., August 1975.

25 *System 2000–Data Management for Transportation Impact Studies.* Gordon Derr, Richard Dodge, and C. Michael Walton, September 1975.

26 *Regional and Community Transportation Planning Issues–A Selected Annotated Bibliography.* John Huddleston, Ronald Linehan, Abdulla Sayyari, Richard Dodge, C. Michael Walton, and Marsha Hamby, September 1975.

27 *A Systems Analysis Procedure for Estimating the Capacity of an Airport: System Definition, Capacity Definition and Review of Available Models.* Edward V. Chambers III, Tommy Chmores, William J. Dunlay, Jr., Nicolau D. F. Gualda, B. F. McCullough, Chang-Ho Park, and John Zaniewski, October 1975.

28 *The Application of Factor Analysis to Land Use Change in a Metropolitan Area.* John Sparks and Jose Montemayor, November 1975.

29 *Current Status of Motor Vehicle Inspection: A Survey of Available Literature and Information.* John Walter Ehrfurth and David A. Sands, December 1975.

30 *Executive Summary: Short Range Transit Improvement Study for The University of Texas at Austin.* C. Michael Walton, May 1976.

31 *A Preliminary Analysis of the Effects of the Dallas-Fort Worth Regional Airport on Surface Transportation and Land Use.* Harry Wolfe, April 1974.

32 *A Consideration of the Impact of Motor Common Carrier Service on the Development of Rural Central Texas.* James S. Wilson, February 1975.

33 *Modal Choice and the Value of Passenger Travel Time Literature: A Selective Bibliography.* Shane Davies and Mark I. Alpert, March 1975.

34 *Forecast of Air Cargo Originations in Arkansas, Louisiana, and Oklahoma to 1990.* Deborah Goltra, April 1975.

35 *Inventory of Freight Transportation in the Southwest/Part IV: Rail Service in the Dallas-Fort Worth Area.* Charles P. Zlatkovich, Mary L. Gorse, Edward N. Kasparik, and Dianne Y. Priddy, April 1975.

36 *Forecast of Waterborne Commerce Handled by Texas Ports to 1990.* Stuart Metz Dudley, April 1975.

37 *Forecast of Refinery Receipts of Domestic Crude Oil from Pipelines in the West South Central States to 1990.* Mary L. Gorse, Dianne Y. Priddy, and Deborah J. Goltra, April 1975.

38 *A Feasibility Study of Rail Piggyback Service Between Dallas-Fort Worth and San Antonio.* Edward N. Kasparik, April 1975.

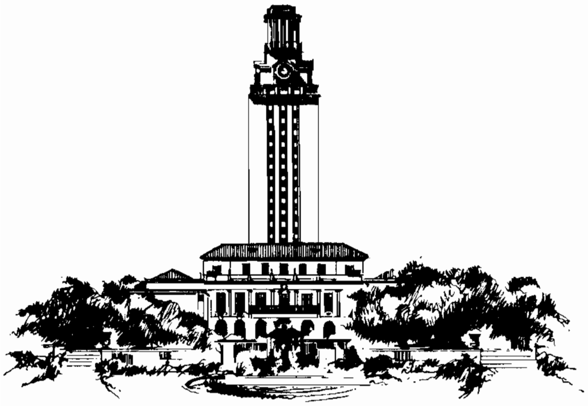
39 *Land Value Modeling in Rural Communities.* Lidvard Skorpa, Richard Dodge, and C. Michael Walton, June 1974.

40 *Towards Computer Simulation of Political Models of Urban Land Use Change.* Carl Gregory, August 1975.

41 *A Multivariate Analysis of Transportation Improvements and Manufacturing Growth in a Rural Region.* Ronald Linehan, C. Michael Walton, and Richard Dodge, October 1975.

42 *A Transit Demand Model for Medium-Sized Cities.* John H. Shortreed, December 1975.

43 *Recommended Procedures for Evaluating Medical Services Transportation in Houston, Texas.* Mark Daskin, John F. Betak, Randy Machemehl, and Ronald Briggs, October 1978.



Council for Advanced Transportation Studies
THE UNIVERSITY OF TEXAS AT AUSTIN