Proceedings of the Conference
STRATEGIC HIGHWAY RESEARCH PROGRAM AND TRAFFIC SAFETY ON TWO CONTINENTS in Gothenburg, Sweden, September 18 – 20, 1991, Part 2

- Roadside Safety Features
- Human Engineering, Training and Traffic Safety
Proceedings of the Conference
STRATEGIC HIGHWAY RESEARCH
PROGRAM AND TRAFFIC SAFETY
ON TWO CONTINENTS in
Gothenburg, Sweden,
September 18 – 20, 1991, Part 2

– Roadside Safety Features
– Human Engineering, Training
and Traffic Safety
Papers presented at the seminar were as follows:
Roadside Safety - A Knowledge-based Approach (Ramache, A);
Safety Barrier Systems in Germany and Temporary Steel-Safety-Barriers (Latest Developments) (Wink, B W);
Side Impact Crash Testing of Highway Safety Hardware (Carney, J F and Ray, M H);
Safety Assessment of Highway Designs (Ray, M H and Troxel, L A);
Importance of Using a Range of Vehicle Weights When Testing a Crash Cushion (Dreznes, M G and Denman, O S);
Reliability of Crash Tests Into Segmented Concrete Barriers (Navin, F P D, Thompson, R, MacNabb, M and Romilly, D);
Safe Road Design as Limit State (Navin, F P D);
International Harmonization of Test and Evaluation Procedures for Roadside Safety Features (Taylor, H W);
Occupant Risk by Different Severity Criteria (Giavotto, V);
Proposed Guidelines for Testing and Evaluating Roadside Safety Features - An Update to NCHRP Report 230 (Ross, H E);
Status of the European Work on Harmonizing Requirements and Test Procedures for Roadside Safety Features (Boussuge, J);
Development of a Methodology for Measuring Improper Seat Belt Use (Grant, B A, Pedder, J B and Schewchenko, N);
Mandatory Hazard Perception Testing as a Means of Reducing Casualty Crashes Amongst Novice Drivers (Hull, M);
Eye Scanning Rules for Drivers - How Do They Compare With Actual Observed Eye Scanning Behavior? (Zwahlen, H T);
Effects of Moderate Heat on Driver Vigilance in a Moving Vehicle (Wyon, D P and Norin, F);
Position Accuracy when Pushing Pushbuttons in a Car as a Function of Car Speed and Location: Implications for Design (Zwahlen, H T and Kellmeyer, D).
PREFACE

The Swedish Road and Traffic Research Institute (VTI) and the US Transportation Research Board (TRB) of the National Research Council were jointly organising this international conference. The objective was to cover the present and future road research with special emphasis on the Strategic Highway Research Program (SHRP), as well as the research concerning drivers and vehicles as related to highway safety.

SHRP is a fully funded, $150 million (US), five year program of research directed at asphalt, concrete and structures, highway operations, and long term pavement performance.

In the sessions on roads there were presentations which highlighted differences between European and US practices and needs, and the discussions were concentrated on how to promote international involvement in SHRP and application of its research, within the areas of Asphalt, Long Term Pavement Performance (LTPP), Highway Operations and Concrete and Structures.

In the different road safety sessions there were presentations of actual research in different countries and discussions of the differences that exist between Europe and the USA, trying to explain the reasons for them and examine whether they are reasonable and acceptable.

Linköping October 1991

Kenneth Asp

Proceedings of the Conference STRATEGIC HIGHWAY RESEARCH PROGRAM AND TRAFFIC SAFETY ON TWO CONTINENTS in Gothenburg, Sweden, September 18-20, 1991:

VTI RAPPORT 372A, Part 1
- Opening
- Motorist Information Systems
- Accident Studies and Safety Management

VTI RAPPORT 372A, Part 2
- Roadside Safety Features
- Human Engineering, Training and Traffic Safety

VTI RAPPORT 372A, Part 3
- Operational Roadway and Workzone Research
- Safety and Mobility of Older Drivers

VTI RAPPORT 372A, Part 4
- Simulation and Measurement of Operator and Vehicle Performance
- Strategies to Increase the Use of Restraint Systems

VTI RAPPORT 372A, Part 5
- Asphalt
- Highway Operations and Concrete and Structures

VTI RAPPORT 372A, Part 6
- Long-Term Pavement Performance

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Helmut T Zwahlen, Ohio University, USA

Effects of Moderate Heat on Driver Vigilance in a Moving Vehicle
David P Wyon, National Swedish Institute for Building Research and Fredrik Norin, Volvo Car Corporation, Sweden

Position Accuracy when Pushing Pushbuttons in a Car as a Function of Car Speed and Location: Implications for Design
Helmut T Zwahlen and David Kellmeyer, Ohio University, USA
STRATEGIC HIGHWAY RESEARCH PROGRAM AND TRAFFIC SAFETY ON TWO CONTINENTS

Gothenburg, Sweden

September 18-20, 1991

WEDNESDAY SEPTEMBER 18

OPENING

9.00 - 11.30

Chairman: Mrs Gunnel Färm, Director General, Swedish Road and Traffic Research Institute (VTI), Sweden

Opening Speeches
Mr Kjell A Mattsson, Governor of the Province of Gothenburg and Bohus, Sweden
Mrs Gunnel Färm, Director General, Swedish Road and Traffic Research Institute (VTI), Sweden

Research and the International Transportation Community
Dr C Michael Walton, Chairman, Executive Committee, Transportation Research Board, National Academy of Sciences and Engineering, USA

Transport Policies and Traffic Safety in an Integrated Europe
Dr Jan C Terlouw, Secretary General of the European Conference of Ministers of Transport (ECMT), France

Getting SHRP's Products Into Practice
Dr Damian J Kulash, Executive Director, Strategic Highway Research Program (SHRP), USA

FHWA Role in SHRP Implementation
Mr E Dean Carlson, Executive Director, Federal Highway Administration, USA
(presented by Charles L Miller)

Recent European Initiatives in Research Collaboration
Mr David F Cornelius, Director, Transport and Road Research Laboratory (TRRL), United Kingdom

VTI RAPPORT 372A
WEDNESDAY SEPTEMBER 18

ASPHALT

13.00 - 17.00

Chairman: Tord Lindahl, Swedish Road and Traffic Research Institute (VTI), Sweden

The Asphalt Model: Results of the SHRP Asphalt Research Program
D R Jones and T W Kennedy, University of Texas, Austin, Texas, USA

SHRP Asphalt-Aggregate Mix Analysis System
T W Kennedy and R J Cominsky, University of Texas, Austin, Texas; E T Harrigan and R B Leahy, Strategic Highway Research Program, Washington, USA

An Investigation of Asphalt-Aggregate Interaction and Their Sensitivity to Water
C W Curtis, L M Perry and C J Brennan, Auburn University, Auburn, Alabama, USA

Thermal Fatigue Cracking of Asphalt Concrete Pavements - An Experimental Approach
N W Jackson, T S Vinson, and V Janoo, Oregon State University, Corvallis, Oregon, USA

Development of Test Methods for a Performance-Related Bitumen Specification
D A Anderson, The Pennsylvania State University, USA

Characterization of Self Assemblies in Asphalt by NMR Spectroscopy and High Performance Gel Permeation Chromatography
P A Jennings, J A S Pribanic, T M Mendes, and J M Smith, Montana State University, Bozeman, Montana, USA

Asphalt Research in The Netherlands
P C Hopman, Delft University of Technology, Delft; P A J C Kunst, Netherlands Pavement Consultants bv, Hoevelaken; A C Pronk and J M M Molenaar, Roads and Hydraulic Department of Rijkswaterstaat, Delft, and A A A Molenaar, Delft University of Technology, Delft, The Netherlands
WEDNESDAY SEPTEMBER 18

MOTORIST INFORMATION SYSTEMS

13.00 - 17.00

Chairman: Conrad Dudek, Texas A&M University, College Station, USA

Changes in Driver Behaviour as a Function of Handsfree Mobile Phones: A Simulator Study
Håkan Alm and Lena Nilsson, Swedish Road and Traffic Research Institute (VTI), Sweden

Variable-MESSAGE Signs: Legibility and Recognition of Symbols
Colomb, Huberg, Bry, Carta, Laboratoire Central des Ponts et Chaussees, Dore-Picard, Institute National de Recherche sur les Transport et leur Securité, France

The Man and His Wheel: Cognitive and Perceptual Factors
Marcel Wierda, Traffic Research Centre, The Netherlands

Measuring Effects of Variable Message Signing on Route-Choice and Driving Behavior
Richard van der Horst, Wiel Janssen and J E (Hans) Korteling, TNO Institute of Perception, Soesterberg, The Netherlands

Acceptance and Benefits of the Berlin Route Guidance and Information System (LISB)
Jürg M Sparmann, SNV Studiengesellschaft Nahverkehr mbH, Berlin, Germany

Automobile Navigation Safety Issues
Robert L French, R L French & Associates, Ft Worth, Texas, USA

(16.30-17.00 Short business meeting of TRB Committee A3B08, User Information Systems - visitors welcome)
WEDNESDAY SEPTEMBER 18

ACCIDENT STUDIES AND SAFETY MANAGEMENT

13.00 - 17.00

Chairman: Gunnar Carlsson, Swedish Road and Traffic Research Institute (VTI), Sweden

Economic Appraisal and Ranking of Road Safety Measures
Karl-Olov Hedman, Swedish Road and Traffic Research Institute (VTI), Sweden

Traffic Safety on Two Continents — A Ten-Year Analysis of Human and Vehicular Involvements
Rüdiger Lamm, University of Karlsruhe, Germany and Elias M Choueiri, North Country Community College, New York, USA

Description and Testing of a Side Impact Protection System
Jan Ivarsson, Volvo Car Corporation, Sweden

A Critical View of Traffic Safety Management in a Developing Country; A Case Study of Jordan
N M Katamine and M A Salem Kiyassat, University of Jordan, Jordan

Development of a Collision Topology for Evaluation of Collision Avoidance Strategies
Kenneth L Campbell, Daniel F Blower, Dawn L Massie, Patricia F Waller and Arthur C Wolfe, UMTRI, Ann Arbor, Michigan, USA

Comprehensive Safety Management
Michael S Collins, Ergotrans, United Kingdom

The Future of Road Traffic Management: Urgent Global Harmonization Will Affect All Governments
Arthur R Olin, Sweden

Implications of Litigation for Highway and Motor Vehicle Safety Research
P Robert Knaff, K B and Assoc., Silver Spring, MD, USA

The Impact of Litigation on the Federal Highway Administration’s Highway Safety Program
Steven E Wermcrantz, Federal Highway Administration, USA
THURSDAY SEPTEMBER 19

ROADSIDE SAFETY FEATURES

9.30 - 17.30

Chairman: Thomas Turbell, Swedish Road and Traffic Research Institute (VTI), Sweden, co-Chairman: Hayes E Ross, Texas Transportation Institute (TTI), USA

Roadside Safety - A Knowledge-based Approach
Abdelkrim Ramache, University of Newcastle Upon Tyne, United Kingdom

Safety Barriers Systems in Germany
Bernd Wolfgang Wink, Volkmann & Rossbach GmbH & Co KG, Germany

Side Impact Crash Testing of Highway Safety Hardware
John F Carney and Malcolm H Ray, Vanderbilt University, Nashville, USA

Safety Assessment of Highway Designs
Malcolm H Ray, Standard & Ray Assoc., Franklin, USA (presented by J F Carney)

The Importance of Using a Range of Vehicle Weights when Testing a Crash Cushion
Michael G Dreznes, Energy Absorption Systems Inc, Chicago, USA

Reliability of Results of Crash Testing Small and Medium Size Cars into Two Segmented Concrete Barriers
Francis P D Navin, University of British Columbia, Vancouver, Canada

13.00 Luncheon

Safe Road Design as Limit State
Francis P D Navin, University of British Columbia, Vancouver, Canada

Status of the United States Efforts in Promoting International Harmonization of Test and Evaluation Procedures for Roadside Safety Features
Harry W Taylor, FHWA, Washington DC, USA

Occupant Risk by Different Severity Criteria
Vittorio Giavotto, Politecnico di Milano, Milan, Italy

Hayes E Ross Jr, Texas Transportation Institute, Texas A&M University, USA

Status of the European Work on Harmonizing Requirements and Test Procedures for Roadside Safety Features
Jacques Boussuge, SETRA, France

WORKSHOP on International Harmonization
Status reports from the ongoing update of the US test procedures and the development of a European Standard within CEN
(This workshop will be followed up in non-public informal meeting between TRB committee A2A04(2) and CEN/TC226/WG1 on Friday morning)

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THURSDAY SEPTEMBER 19

HUMAN ENGINEERING TRAINING AND TRAFFIC SAFETY

9.30 - 13.00

Chairman: Alison Smiley, Human Factors North Inc, Toronto, Canada

Development of a Methodology for Measuring Improper Seat Belt Use
Brian A Grant, Road Safety Directorate, Transport Canada, Jocelyn Pedder and
Nicholas Shewchenko, Biokinetics and Assoc. Ltd, Ottawa, Canada

Mandatory Hazard Perception Testing as a Means of Reducing Casualty Crashes
Amongst Novice Drivers
Michael Hull and Peter Lowe, Vic Roads, Australia

Eye Scanning Rules for Drivers - How Do They Compare With Actual Observed Eye
Scanning Behavior?
Helmut T Zwahlen, Ohio University, Athens, Ohio, USA

The Effects of Moderate Heat on Driver Vigilance in a Moving Vehicle
D P Wyon and F Norin, Volvo Car Corporation, Sweden

Position Accuracy When Pushing Pushbuttons in a Car as a Function of Car Speed
and Location: Implications for Design
Helmut T Zwahlen, Nuruddin Abdullah and David Kellmeyer, Ohio University,
Athens, Ohio, USA

(9.00-9.30 Short meeting of TRB Committee A3B02, Vehicle User Characteristics -
visitors welcome)
THURSDAY SEPTEMBER 19

OPERATIONAL ROADWAY AND WORKZONE RESEARCH

14.00 - 17.30

Chairman: Karl-Olov Hedman, Swedish Road and Traffic Research Institute (VTI), Sweden

Overtaking Behaviour on Single Carriageway Roads in the United Kingdom
J G Hunt and T A Mahdi, School of Engineering, UWCC, Cardiff, United Kingdom

Overtaking Behaviour on Two-Lane Rural Roads
Arne Carlsson, Swedish Road and Traffic Research Institute (VTI), Sweden

Time and Space Criteria of Column Following
Milan Vujanic, University of Belgrade, Yugoslavia

Passing Operations on a Recreational Two-Lane, Tow-Way Highway
A R Kaub, University of South Florida, Tampa, USA

Reducing Risk Taking in Passing on Two Way Roads
Krsto Lipovac, Higher School of Internal Affairs, Yugoslavia

Guidelines for Railroad Preemption at Signalized Intersections
Peter S Marshall, Barton-Aschman Ass Inc, Minneapolis, MN and William D Berg, University of Wisconsin-Madison, USA
THURSDAY SEPTEMBER 19

SIMULATION AND MEASUREMENT OF OPERATOR AND VEHICLE PERFORMANCE

9.30 – 13.00

Chairman: R Wade Allen, Systems Technology Inc, USA

Traffic Measurements by Means of Computer Vision Techniques
N O Jørgensen, Institute of Roads, Transport & Town Planning, Denmark

Dynamic 3-D Highway Modelling
Arthur Roberts, NJDOT Research, Trenton, USA (Presented by R Pain)

Validation of Real-Time Man-In-The-Loop Simulation
R Wade Allen, David G Mitchell, Anthony C Stein and Jeffery R Hogue, Systems Technology Inc, Hawthorne, USA

Measurement of Driver Performance in Training Simulators
J E Korteling, TNO, The Netherlands

Litigation and Driving Simulators
Slade Hulbert, Ph D, Consultant, Danville, USA

STRATEGIES TO INCREASE THE USE OF RESTRAINT SYSTEMS

WORKSHOP

14.00 – 17.30

14.00 Opening

14.05 Illustration of background paper

14.15 National reports on seat belt use and countermeasures (10 minutes each)
- Canada
- Finland and other Nordic countries
- France
- Germany
- Great Britain
- Netherlands
- United States

Tapani Mäkinen

Brian A Grant
Juha Valtonen
Yves Page &
Sylvain Lassarre
Hans Ch Heinrich
Jeremy Broughton
Marjan Hagenzieker
Robert Knaff

15.45 Coffee break

16.00 Discussion with speakers and audience

17.00 Concluding remarks and closure

(17.00-17.30 Short business meeting of TRB Committee A3B06, Simulation and Measurement of Operator and Vehicle Performance)
THURSDAY SEPTEMBER 19

LONG-TERM PAVEMENT PERFORMANCE

9.30 – 17.30

Chairman: Hans Jørgen Ertman Larsen, Danish Road Institute, Denmark

Early Evaluations of SHRP LTPP Data and Planning for Sensitivity Analyses
J B Rauhut, Brent Rauhut Engineering, Austin, Texas; M I Darter, Eres Consultants Inc, Savory, Illinois; O Pendleton, Texas A&M University, College Station, Texas; and N F Hawks, Strategic Highway Research Program, Washington, USA

The Specific Pavement Studies: Key Issues and Potential Products
A N Hanna and N F Hawks, Strategic Highway Research Program, Washington, USA

Expected Changes to the AASHTO Design Guide
N F Hawks, Strategic Highway Research Program, Washington, USA

Cost Effectiveness of Asphalt Concrete Overlays – The Canadian Approach
G A Sparks, Clayton, Sparks & Ass Ltd, Saskatoon, Canada; D M Nesbitt, Decision Focus Inc, Los Altos, California; and G Williams, Roads and Transportation Association of Canada, Ottawa, Canada

Long Term Pavement Performance Trials and Data Analysis in The United Kingdom
H R Kerali, University of Birmingham and J F Potter, Transport and Road Research Laboratory, United Kingdom

SHRP—NL: A Research Project Parallel to SHRP
G T H Sweere, SHRP—NL, Delft, The Netherlands

Structural Assessment, Performance and Economic Maintenance of Minor Roads
J Roger Duffell, The Hatfield Polytechnic, United Kingdom

Treatment of Bearing Capacity Results
B Leben and A Petkovsek, Institute for Geotechnic and Roads, Ljubljana, Yugoslavia

A Model of IRI for Jointed Plain Concrete Pavements
P Ceza, J David, J Gonzalez and M Poblete, IDIEM, University of Chile; and P Gutierrez, National Highway Administration, Chile

The High Speed Road Deflection Meter
P W Arnberg and G Magnusson, Swedish Road and Traffic Research Institute (VTI), Sweden

PAVUE: A Real-Time Pavement Distress Analyzer
M W Burke and K Råhs, OPQ Systems AB, Linköping; and P W Arnberg, Swedish Road and Traffic Research Institute (VTI), Sweden
FRIDAY SEPTEMBER 20

SAFETY AND MOBILITY OF OLDER DRIVERS

8.30 - 12.30

Chairman: John Eberhard, TRB Task Force on Safety and Mobility of Older Drivers, USA

Old Hands on the Wheel: Exposure, Accident Experience and Problems of Elderly Drivers
M L Chipman, C G MacGregor, A M Smiley, University of Toronto, M E H Lee-Gosselin, Université Laval, Quebec, and L Clifford, Ministry of Transportation, Toronto, Canada

More Safety Thanks to Good Orientation — Nothing Works Without Traffic Signs
Henriette Reinsberg, 3M Germany, Germany

Elderly People and Mobile Telephone Use — Effects of Driver Behaviour?
Lena Nilsson and Håkan Alm, VTI, Sweden

Drinking Performance in Mild Senile Dementia of the Alzheimer Type (SDAT)
Linda Hunt, Dorothy Edwards, John C Morris and Ada Mui, Irene Walter Johnson Rehabilitation Institute at Washington University Medical Center, St Louis, USA

Discussant:
Robin Barr, National Institute on Aging, US Department of Health and Human Services, Bethesda, Maryland, USA

SYMPOSIUM SESSION:

VISUAL AND COGNITIVE CAPABILITIES IN OLDER DRIVERS: PREDICTING ACCIDENT RISKS

Visual Function and Eye Health: Their Relationship to Older Driver Problems
Michael Sloane, University of Alabama at Birmingham, USA

Attentional and Cognitive Factors in Predicting Older Driver Problems
Karlene Ball, Western Kentucky University, Bowling Green, USA

Attention and Driving Performance in Alzheimer’s Dementia
Raja Parasuraman, Catholic University of America, Washington, USA

Older Drivers Handling Road Traffic Informatics: Divided Attention in a Dynamic Driving Simulator
Peter C van Wooffelaar, Wiebo H Brouwer and Talib Rothengatter, Traffic Research Centre, University of Groningen, The Netherlands

Discussant:
Harvey Sterns, Institute for Life-Span Development and Gerontology, University of Akron, Ohio, USA

VTI RAPPORT 372A
FRIDAY SEPTEMBER 20

SAFETY AND MOBILITY OF OLDER DRIVERS

13.30 – 16.00

PANEL DISCUSSION:

FEASIBILITY OF INTERNATIONAL PERFORMANCE STANDARDS FOR OLDER DRIVERS

Presiding Officer: John Eberhard, Chairperson, TRB Task Force on Safety and Mobility of Older Drivers, USA

1. A USA Perspective
   Robin Barr, National Institute of Aging, Bethesda, MD, USA

2. A European Community Perspective
   Margaret Greico, Oxford University, United Kingdom
   Kay Axhausen, Imperial College of Science, Technology and Medicine, London, United Kingdom

3. A Scandinavian Perspective: Older Drivers – A Problem for Whom?
   Krister Spolander, Central Bureau of Statistics (SCB), Sweden

4. A Multi-continent Perspective
   Martin Lee-Gosselin, Université Laval Quebec, Canada

Discussion: Invited from prior presenters and all session attendees

(16.00-16.30 Short meeting of TRB Task Force A3T52, Safety and Mobility of Older Drivers, visitors welcome)
Chairman: Torkild Thurmann-Moe, Road Research laboratory, Norway

Closed Track Testing of Maintenance Work Zone Safety Devices
S C Shah, Strategic Highway Research Program, Washington and F R Hanscom, Transportation Research Corporation, Haymarket, Virginia, USA

Innovative Materials for Pavement Surface Repairs: Field Installation and Evaluation
S C Shah, Strategic Highway Research Program, Washington, USA

MINSALT - A 5-Year Study to Minimize the Negative Effects of Salt
Kent Gustafson and Gudrun Öberg, Swedish Road and Traffic Research Institute (VTI), Linköping, Sweden

Deicing Salt - Its Use and Effect on Road Safety and the Living Conditions of Roadside Trees and Shrubs
Siegfried Giesa, Technical University of Darmstadt, Germany

Improving Concrete Pavements Through SHRP Research
Amir N Hanna, Strategic Highway Research Program, Washington, USA

Optimization of Highway Concrete Through Combined Use of Particle Packing Modelling, Rheological Studies, Computer Simulations and Compaction Simulations
J Holm and P J Andersen, G M Idorn Consult A/S, Birkerød, Denmark

High Performance Road-Surfacing Concrete with Good Resistance to Wear by Tyre Studs
Mårten Nilsson, Swedish Road Administration, Sweden

Maintenance and Repair of Highway Concrete Bridges: A Case Study
I Al-Babatain and A M Abbas, Ministry of Communications, Riyadh, Saudi Arabia
Ekberg Bengt
Ekholm Leif
Ellebaek Ellen
Engervall Dag
Englund Anders
Eriksen Kirsten
Eriksson Ingmari
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Foley Paul
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Fredriksson Rune
French Robert L
Fåhraeus Gunnel
Garcia Rios Fernando
Giavotto Vittorio
Giesa Siegfried
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Hakamies-Blomqvist Liisa
Haldorsen Ivar
Hanna Amir N
Hanscom Fred
FAS Service AB
Fibertex Aps
Trygg Hansa SPP Protectum
Danish Road Institute
Danish Road Institute
Nynäshamn Bitumen AB
Norwegian Car Ass.
Atari Games Corporation
SHRP
RL French & Assoc.
VTI
Bionda J.A
Dipartemento Di Ingegneria
Technical University Darmstadt
University of Liverpool
Superfor Construction A/S
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VTI  
SWEDEN

Öster Roland  
Nynäts Bitumen Tech.  
SWEDEN
Roadside Safety – A Knowledge-based Approach

Abdelkrim Ramache
Transport Operations Research Group
University of Newcastle upon Tyne
United Kingdom
Roadside Safety — A Knowledge-based Approach

A. RAMACHE

TRANSPORT OPERATIONS RESEARCH GROUP
UNIVERSITY OF NEWCASTLE UPON TYNE

ABSTRACT

Every time vehicles leave the road they are likely to collide with fixed roadside objects, such as lighting columns, signposts, etc. Traffic and highway engineers have always been faced with the difficult task of making important decisions regarding the selection and implementation of roadside safety improvements. To facilitate their decisions, a knowledge-based system called ROSDIS (ROADside Safety Design and Improvement System) has been developed. This paper describes the knowledge-based system which constitutes a significant extension of an existing model and uses system safety methodology. A fault tree depicting the process behind any single vehicle roadside accident has been implemented in a prototype program written in Prolog, which has since been refined.

Since the most important part of the fault tree lies in the determination of the probabilities of basic underlying events, consideration was given to how they can be related to available and measurable data. An analysis of single vehicle roadside accident data has been carried out. The objective here is to extract information from the available data, so it can be utilised by the system. Accidents records do not provide all the necessary information on the engineering aspect of single vehicle roadside accidents. This lack of information led to the design and implementation of a field procedure to collect the missing data manually (i.e. measurements of the lateral distances from the edge of the pavement to the fixed roadside objects that have been involved in collisions).

The system enables the user to experiment with different configurations of fixed roadside objects and select the configuration which minimises the probability of collision. The explanation facility of the system allows the user to see why a question is asked by the system and how the probability of collision was reached. The result of this research should eventually be a quantitative design tool through which a risk situation at the roadside can be assessed and safety decisions made concerning the locations and types of roadside objects.

In addition to presenting ROSDIS, the paper will discuss the differences between the present study in the Tyne and Wear area (United Kingdom) and previous studies that have been conducted in the United States.
I. INTRODUCTION

Single vehicle roadside accidents happen every time vehicles encroach on the roadside and collide with fixed objects (such as lighting columns, signposts, etc.). It is obvious that these objects constitute potential hazards to out-of-control vehicles and their occupants. Fixed roadside objects are not hazards by themselves. However, because of their placement along the road and the nature of their design, they increase their probability of being struck by errant vehicles causing fatal or serious injuries to their occupants.

The objective of the research work presented here is to develop a knowledge-based system to overcome some of the difficulties faced by traffic and highway engineers in their decision-making process regarding the location of fixed roadside objects. Saving lives and reducing the frequency and severity of single vehicle roadside accidents by considering alternative configurations of fixed roadside objects are valuable goals of a knowledge-based system. The power of any knowledge-based system lies in its knowledge base and there is a possibility of combining existing domain knowledge from many sources into a shared knowledge base. The synthesis of this knowledge will provide a new way of solving this problem.

Another reason for building such a system is that roadside safety is a specific problem that suits the constraints of a knowledge-based system and single vehicle roadside accidents pose a common problem that can benefit significantly from intervention.

There is a sizable body of knowledge directed to the specific aspect of roadside safety. Unfortunately this knowledge by itself is not sufficient since its possession does not guarantee necessarily its application. The gap between acquiring this knowledge and putting it into practical use has become so great that it has been very often questioned whether further research is still required before applying the existing knowledge. However, additional research concerning the application of information technology is needed.

A review of roadside literature produced few recent references that can be considered as making a major contribution to this area of traffic safety. These studies were analysed and synthesised in an attempt to provide a body of knowledge to be encapsulated into a knowledge-based system. A roadside hazard model derived from the roadside hazard concept and fault tree analysis, an important system safety technique, are used to power this system.

It is widely recognised that the combination of many sources of knowledge in a knowledge-based system for problem solving has a strong effect on the quality of performance of a system. As research proceeded, additional knowledge that could be incorporated into the system was identified.

II. THE PROBLEM SOLVING PROCESS

What has been lacking in most of the previous traffic safety research, whether concentrating on accidents or accident prevention, has been comprehensiveness. The present research was designed to overcome this deficiency. Its ultimate objective was to establish a link between system safety methodology and the knowledge-based system concept, and show how comprehensiveness and problem solving capability (two important characteristics of these two powerful tools) can be combined to tackle the single vehicle roadside accident problem.
The intent of the approach suggested here is to provide a coherent framework for this area of traffic safety where the problem is recognised and treated as an integral whole. All knowledge already gained in the field can be organised in a usable form and lack of specific information identified. The problem solving process is diagrammatically shown in Figure 1.

Figure 1

**PROBLEM SOLVING PROCESS (12)**

This diagram illustrates the various types of knowledge to be incorporated into the expert system and points out how the problem solving process can be viewed as a flow of reasoning leading to the solution of the problem. It can be summarised as follows: The system is written in the programming language Prolog and makes extensive use of accident analyses (accident cause-consequence analysis, fault tree analysis and statistical analysis of single vehicle roadside accidents).

A problem which frequently arises while trying to solve a real-world problem using a knowledge-based approach is that a piece of information is not available to the system although it is essential to its operation. One way of dealing with the missing information is to rely on findings from previous studies. Another way is to design and implement a field procedure to collect data leading to the relevant information. A better way, of course, is to build and maintain databases where the needed information is stored.
III. THE ROADSIDE HAZARD MODEL

The model considers the relationship between an encroaching vehicle and a roadside obstacle. The main idea here is to determine the area along a road (called also the hazard envelope) within which a vehicle leaving its travelway at a prescribed angle will strike a fixed roadside object. Figure 2 shows the hazard envelope. It is divided into four basic ranges. The first and fourth ranges account for the double contribution of the length \( C/\sin \theta \) to the total exposure length (TEL) and correspond to impacts on the corners of the obstacle.

Figure 2

RELATIONSHIP BETWEEN A RECTANGULAR ROADSIDE OBSTACLE AND AN ENCROACHING VEHICLE (8)

The second range corresponds to a vehicle striking the side of the obstacle perpendicular to the road and is a function of the width of the obstacle. The third range corresponds to a collision involving the side of the obstacle parallel to the road and has the same length as the obstacle itself. As shown in Figure 2, vehicles are assumed to encroach along a straight path to the obstacle and obstacles are rectangular. Since not all obstacles encountered along the road are rectangular, the model has been extended to handle circular objects as well. A hazard envelope for a circular object is shown in Figure 3.

IV. SYSTEM SAFETY ANALYSIS TECHNIQUES

System safety evolved from system analysis techniques that have been devised to maximise system design. The intended use of these techniques has been to enable decision-makers to reach correct conclusions using an orderly process of data collection and modelling. System safety methodology requires a logical examination of all elements of the system (such as roadside-vehicle-obstacle) identifying all possible sources of accidents. The analysis does not end with the identification of system hazards (roadside hazards). It estimates the probability of accident occurrences and points out the measures available for their elimination. It is quite common in traffic safety practices to wait until accidents happen and analyse them to find their causes. The system safety approach to roadside safety is, however, mainly preventive. Through hazards identification
and methods of analysis, all possible unsafe conditions and practices can be detected and either eliminated or treated before accidents occur. System safety is hardware oriented. Its focus is mainly on the system (i.e. the roadside and the fixed objects).

There are several methods of analysis in use in system safety. Accident cause-consequence analysis and fault tree analysis will be applied here.

IV.0.1 Accident cause-consequence analysis

It is recognised that most accidents have an identifiable sequence of events associated with them. During the examination of a roadside, it appears that a single vehicle roadside accident might happen at different lateral distances from the edge of the pavement to the fixed obstacles. For ease of processing and analysis, objects were assigned to three adjacent bands running parallel to the edge of the pavement (the shoulder width being included) to describe the area in which an errant vehicle can possibly hit a fixed object.

For such an accident to happen in band 1, a vehicle must first encroach on the roadside, not stop or recover in band 1 until it meets an obstacle lying in its trajectory. In band 2, the vehicle must also encroach on the roadside, not stop or recover in both band 1 and band 2, miss obstacles in band 1 until it collides with an obstacle within band 2 lying in its trajectory. Finally an accident will happen in band 3, if a vehicle does not stop or recover in band 1, band 2 or band 3, misses obstacles in both band 1 and band 2 until it strikes an obstacle within band 3 lying in its trajectory. Although simple and direct this method is useful because it provides a step-by-step procedure for listing all possible events that may lead to the undesirable event (the collision). From it a fault tree can be built with a single vehicle roadside accident as its top event.

IV.0.2 Fault tree analysis

Fault tree analysis is a technique that uses logic diagrams to trace all the contributory events that might lead to the event to be prevented or whose probability is to be reduced (in this
case, collision with a fixed roadside object). There are many symbols to draw fault trees, of which three only will be used here: the rectangle, the diamond and the circle. The rectangle identifies events that will generally require further development during the analysis. The diamond is used for events that cannot be developed further because of lack of information (data) or because there is no need to develop them further. The circle is used to describe events that cannot be developed further and are therefore basic.

The fault tree analysis then reasons backward and the contributory events are combined hierarchically by gates. Here again two gates only will be used, the AND gate and the exclusive OR gate. The AND gate indicates that all the contributory events connected to that gate must coexist to cause the event above it. The exclusive OR gate stipulates that the next events cannot logically occur simultaneously. Figure 4 shows a fault tree depicting a single vehicle roadside accident. This fault tree differs from the one built by Horodnicianu (8), two more events were introduced and the diamond was used instead of a circle for some events to show where information is still lacking.

Note that traversing the tree down indicates causes and moving up will indicate the effects. Probabilities were assigned to each event of the fault tree. Since each logic gate represents a numerical operation (multiplication for AND and addition for OR). The fault tree of Figure 4 can be summarised by the following equation:

\[ P_{\text{top}} = P_e(P_{nr1}P_1 + P_{nr1}M_1P_{nr2}P_2 + P_{nr1}M_1P_{nr2}M_2P_{nr3}P_3) \]

with \( M_1 = 1 - P_1 \) and \( M_2 = 1 - P_2 \)

**IV.0.3 Determination of the probabilities of the basic events**

The most important part of the fault tree lies in the determination of the probabilities of the basic events located at the bottom of the fault tree and how they can be related to available and measurable data. These probabilities are very often difficult to obtain although they are required for computing the probability of the top event.

**IV.0.4 Probability that some obstacle lies within the path of an encroaching vehicle**

From Figure 2 it can be seen that the total exposure length (TEL) parallel to the edge of the pavement and in which an encroaching vehicle must not be in order to avoid an obstacle corresponds to the sum of the lengths of the four ranges previously mentioned. So

\[
\begin{align*}
TEL_{ro} &= 2C \csc \theta + d \cot \theta + W \quad \text{for a rectangular object and} \\
TEL_{co} &= 2(C + R) \csc \theta \quad \text{for a circular object.}
\end{align*}
\]

If a road section of length L is considered, The corresponding probabilities for these two types of objects will be:
Figure 4
FAULT TREE DEPICTING A SINGLE VEHICLE ROADSIDE ACCIDENT

Single vehicle roadside accident (Psvr)

Vehicle strikes roadside obstacle (Pso)

Vehicle encroaches on roadway file (Pe)

Vehicle strikes obstacle in Band 1 (Pv1)

Vehicle does not recover in Band 1 (Pnr1)

Vehicle strikes obstacle in Band 2 (Pv2)

Vehicle does not recover in Band 2 (Pnr2)

Vehicle strikes obstacle in Band 3 (Pv3)

Vehicle does not recover in Band 3 (Pnr3)

Obstacle in Band 1 lies in the path of vehicle (P1)

Obstacle in Band 2 lies in the path of vehicle (P2)

Obstacle in Band 3 lies in the path of vehicle (P3)

Vehicle misses obstacle in Band 1 (Mv1)

Vehicle misses obstacle in Band 2 (Mv2)

Vehicle misses obstacle in Band 3 (Mv3)

Vehicle does not recover in Band 1 (Pnr1)

Vehicle does not recover in Band 2 (Pnr2)

Vehicle does not recover in Band 3 (Pnr3)
The ratio of the summation of the total exposure lengths of all obstacles in each band to \( L \) will yield an estimate of the probability that a fixed object will lie in the trajectory of an out-of-control vehicle in that particular band. The corresponding probability is then:

\[
P_t = \sum_{i=1}^{N} \frac{2C \csc \theta + d_i \cot \theta + W_i}{L}
\]

The probability that an encroaching vehicle will collide with a fixed object depends on the number, size and location of the fixed objects on the roadside; the width of the vehicle and the angle of encroachment. The more objects there are along the roadside, the greater the probability of collision will be.

There are situations where fixed objects in the roadside are positioned so close to each other that their respective total exposure length will overlap. To account for this, the length of overlap between each successive pair of objects must thus be subtracted from the summation of equation (1). If objects are numbered from left to right according to increasing \( x - h \cot \theta \), where \( x, h \) and \( \theta \), are as defined in Figure 2 and Figure 3, then the overlap between objects \( i \) and \( i+1 \) in band 1 is:

\[
O_{i,i+1} = 0.5(TEL_i + TEL_{i+1}) - (x_{i+1} - x_i) + (h_{i+1} - h_i) \cot \theta
\]

The total overlap in band 1 \( (TO_1) \) is expressed by:

\[
TO_1 = \sum_{i=1}^{N_1-1} 0.5(TEL_i + TEL_{i+1}) - (x_{i+1} - x_i) + (h_{i+1} - h_i) \cot \theta
\]

The equations developed by Horodnicianu (8) did not consider overlap between bands, to take it into account the following formulation was developed:

\[
U_j = \sum_{i=1}^{N_j} \frac{TEL_i}{L} - \sum_{i=1}^{N_{j-1}} K_i \frac{TO_i}{L}
\]

where \( U_j \) is the probability of a roadside object lying in the path of encroaching vehicle in band \( j \) \((j = 1, 2, 3)\) and

\[
K_i = \begin{cases} 
0, & \text{if } TO_i \geq 0; \\
1, & \text{otherwise.}
\end{cases}
\]
\[ P_1 = U_1 \]
\[ P_2 = U_2 - U_1 \]
\[ P_3 = U_3 - U_2 \]

with

\[ N_1 = \text{Number of objects in band 1} \]
\[ N_2 = \text{Number of objects in band 2} \]
\[ N_3 = \text{Number of objects in band 3} \]

**IV.0.5 Probabilities of non-recovery**

The probabilities of non-recovery \( P_{nr1}, P_{nr2} \) and \( P_{nr3} \) are functions of the characteristics of the roadside section under consideration. In the case where data on encroachments in which vehicles either recovered or were involved in accidents exist, they can be computed. But most of the time data of this nature are not available and the analyst has to rely on previous studies done in this area for their estimation (18).

**IV.0.6 Probability of encroachment**

An estimate of \( P_e \), The probability of encroachment can be obtained from the following formula (8):

\[
\frac{\text{encroachments/km/year}}{\text{section length}(L)} \times \frac{\text{ADT}}{365}
\]

It is expected that values obtained for \( P_e \) will be very small and will not represent true probabilities. The structure of the fault tree permits the factoring out of \( P_e \) when a specific road section is studied. We are more concerned here in the relative probabilities of single vehicle roadside accidents and their differences rather than with absolute values; therefore the effect of \( P_e \) is not relevant.

**V. THE KNOWLEDGE-BASED SYSTEM**

While knowledge-based systems have been traditionally built using large collections of rules based on empirical associations, interest in systems that reason from first principles has increased. Hart (7), considered the potential enhanced performance of systems having a multi-level design. He contrasted surface-level models and deep-level models of reasoning describing a hypothetical system using a multi-level approach. The deep-level model is purely mathematical, while the surface model is of the production rule type. Recent knowledge-based systems literature has started to advocate and use causal models (12,4).

The type of knowledge within a system determines its architecture. Although few classifications have been offered in the literature (14), for the purpose of this study the distinction will be
made between systems based on empirical associations with *shallow knowledge* and systems based on causal models with *deep knowledge*. Giovannini and Malabocchia (4) referred to mixed mode systems mentioning the limitations in each of the two approaches. To surmount these limitations, the authors suggest the combination of both approaches in a single system.

The proposed system is a significant extension of an existing model (5,8), and uses system safety methodology. Accident cause-consequence analysis and fault tree analysis are used to represent the process behind any single vehicle roadside accident. Qualitative analysis is used first, then quantitative evaluation is performed to estimate the probability of occurrence of the *top event* of the fault tree (in this case collision with a fixed roadside object) in terms of the probabilities of the basic events located at the bottom of the fault tree. Once this probability is computed, tests on changes in the roadside environment are carried out. The removal, relocation, protection by attenuating devices or use of other forms of roadside objects such as breakaway will result in a change of the probabilities of the basic events and thus in the probability of the *top event* and the severity of this type of accident. The amount by which that probability is reduced will provide a measure of the effectiveness of the action taken.

V.0.1 System description

The system that will be described here can be thought of as a computer system which simulates the action of an *expert* in roadside safety. It is both, model-based and rule-based system written in Prolog. This system uses the concept of meta-interpreters (16,17) which are a class of meta-programs. Meta-programs are themselves programs that treat other programs as data meaning that they can be analysed, transformed and simulated. A meta-interpreter for Prolog is then an interpreter for Prolog written in the language itself.

V.0.2 System implementation

It was decided from the beginning of this research to implement the system on a micro-computer so it can be used in many locations. The fault tree of Figure 4 and the roadside hazard model (Figures 2 and 3) have been implemented in a prototype program written in Prolog, which has since been refined and extended. Prolog was found useful as the implementation language for a number of reasons. It is well suited for building knowledge-based systems and many of its features make it convenient for their development. It is also quite easy to build data structures with Prolog. Prolog provides also powerful means for searching, pattern matching and list manipulation which can handle very complex tasks. Prolog contains structures more suitable for writing programs that evaluates logical expressions (such as fault tree). The programming was designed to run on an IBM-PC/AT under Prolog-2 from Expert Systems International.

V.0.3 System architecture

The two main components that can usually be distinguished in the structure of a knowledge-based system are the knowledge base and the inference engine (19). This decomposition is not quite appropriate for knowledge-based systems written in Prolog. The new decomposition illustrated by: *Knowledge-based system = Knowledge + Meta-interpreter* (16) was used to implement the fault tree of figure 4 as a knowledge-based system.
Interaction between the program and the user and an explanation facility for why and how queries, two important features expected of knowledge-based systems, were added (19). A database for the description of all objects in a roadside was also included. The internal structure of the knowledge-based system is illustrated by Figure 5 which shows the interaction between the five main modules composing the system. The arrows show the flow of information between them.

**Figure 5**

**INTERNAL STRUCTURE OF THE SYSTEM**

<table>
<thead>
<tr>
<th>Meta-Interpreters</th>
<th>Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>The explanation facility consists of two shells:</td>
<td>Information screen1</td>
</tr>
<tr>
<td>- &quot;Why&quot; (a question is asked); and</td>
<td></td>
</tr>
<tr>
<td>- &quot;How&quot; (the Peru is reached).</td>
<td></td>
</tr>
</tbody>
</table>

- **Roadside Hazard Model**
  - Assigns objects to bands
  - Sorts objects \( (x - 
    \theta \text{or} \text{Theta}) \)
  - Computes TEL for each object
  - Tests for overlap between adjacent objects
  - Computes probability of exposure for each object
  - Computes \( P_1, P_2 \) and \( P_3 \)
  - Computes average \( P_1, P_2 \) and \( P_3 \)
  - Using the distribution of angle of encroachment and \( P_1, P_2 \) and \( P_3 \)

- **Database**
  - Static Database
    - Objects description
    - Roadsides section length
    - Vehicle width
    - Band width
    - Midpoint values for intervals
    - Dynamic database
    - Asserted (added) objects
    - Extracted (removed) objects
  - Number of encroachments per km per year
  - Average daily traffic (ADT)

**V.0.4 Data Requirements for the system**

The data required by the system can be subdivided in four groups:

1. **Objects description.**
2. **Average daily traffic (ADT).**
3. **Number of encroachments per km per year.**
4. **Probabilities of non-recovery in the various bands \( P_{nr1}, P_{nr2} \) and \( P_{nr3} \).**

**V.0.5 Inputs and outputs**

At this development stage, the inputs required for the knowledge-based system are:
- widths \( (d_i) \) and lengths \( (W_i) \) for rectangular objects;
- radii \( (R_i) \) for circular objects;
- longitudinal distances of objects \( (x_i) \);
- lateral distances \( (h_i) \);
- vehicle width \( (C) \);
- average daily traffic \( (ADT) \) and
- the number of encroachment per km per year for the road section under study;
- the probabilities of non-recovery in each band \( P_{nr1}, P_{nr2} \) and \( P_{nr3} \).

A first version of the program was developed where the angle of encroachment \( \theta \) appeared as one of the inputs to the system. However, the angle with which a vehicle encroaches on the roadside is not known and most of the time impossible to determine. It was decided to remove it from being an input to the system. An approximation based on previous distribution of
encroachment angles \((9)\) to compute the expected probabilities of an object lying in the path of an out-of-control vehicle \(P_1, P_2,\) and \(P_3,\) was used.

Statistical analyses have shown that cars (4 wheels) are among the vehicles the most involved in this type of accident and front impacts are the most frequent \((11,15)\). This type of information could for instance be used to estimate the width of vehicle \((C)\). Accident records can also be used to determine the number of encroachment per km per year given that road section lengths are available.

Accident records do not provide all necessary information on the engineering aspect of single vehicle roadside accidents. For the purpose of the present study, this lack of information led to the design and implementation of a field procedure to collect the missing data manually. The results of the field procedure are summarised by Figure 6. The number of measurements taken was limited due the difficulties in this type of data collection. 195 cases only were considered. The curve obtained by joining all the points is quite similar to the ones derived from previous studies \((9,18)\). This curve describes the nature of the roadsides on which these accidents happened. No information regarding the minimum safest distance between the edge of the pavement and fixed roadside objects is suggested. However, there are strong indications that relatively safer roadsides can be developed by providing a recovery area up to at least 3 metres from the edge of the pavement.

**Figure 6**

DISTANCE FROM EDGE OF PAVEMENT TRAVELLED BY OUT OF CONTROL VEHICLES \((13)\)

The relationship between the distance and the percentage of fixed-object accidents has been studied previously in the United States \((20)\). Figure 7 shows this relationship. It summarises the results of a field survey of the distance from the roadway of roadside hazards conducted in Georgia at 300 sites of fatal crashes into fixed objects.

From the above data, the system will generate:
Figure 7
DISTANCE OF OBJECTS FROM ROADSIDE AT CRASH SITES (20)

- the probability of an obstacle being in the path of an encroaching vehicle \( P_1, P_2, P_3 \) for each band.

- the probability of having a single vehicle roadside accident given that a vehicle encroaches on the roadside section under consideration \( P_{\text{tera}} \).

V.0.6 A sample session with the system

When the system is started it presents the user with a series of questions (one at a time) to which he is expected to give a full answer. Every time a question is displayed, two options are available. The user can in return either ask why, the system is asking a given question or type in the value of the required parameter followed by a dot. If the user decides to ask why, the system will explain why it needs the information in order to carry on. If on the other hand the user inputs the appropriate number, the system proceeds by asking other relevant information until the probability of having having a single vehicle roadside accident in the road section under study is determined. The user can then ask how, the system will enable him this time to see how the solution was reached.

A feature of most knowledge-based systems is that they do not have built into them all information necessary to their operation. Therefore the user must be asked to supply the missing information. The following questions are asked by the system:
What is the number of encroachments per km per year?

What is the average daily traffic?

What is the probability of non-recovery in band 1 ($P_{nr1}$)?

What is the probability of non-recovery in band 2 ($P_{nr2}$)?

What is the probability of non-recovery in band 3 ($P_{nr3}$)?

The user must supply the number of encroachments per km per year which can be derived from previous accident history. However, under reporting presents a major problem for this type of accident since the frequency of encroachments is underestimated. The average daily traffic (ADT) can be obtained from traffic counts. The user must also supply the probabilities of non-recovery in the various bands. Fortunately researchers have produced predictive graphs for estimating the benefits of removing fixed roadside obstacles. Among these graphs, the one developed by Stonex at General Motors Proving Ground (18) and shown in Figure 8 seems to be the ideal for the purpose of this study. This graph can be used to estimate the probabilities of non-recovery provided that the following assumption is made: a lateral movement that equals or exceeds a given distance represents a non-recovery up to that distance. It must be noted that the General Motors study is the only one of its kind.

**Figure 8.**

GENERAL MOTORS PROVING GROUND "HAZARD" CURVE (18)

The system has been tested using data from previous studies (9). The values obtained for the probability of single vehicle roadside accident $P_{err}$ have shown that beyond a certain value of the average daily traffic (6000 vehicles per day) the $P_{err}$ remains practically constant. This result is quite interesting since most past research has shown that single vehicle roadside accidents have the tendency to occur on roads with low traffic volumes (10,6,3).
VI. CONCLUSION AND FURTHER WORK

The use of system safety holds great promise for the future, especially when combined with the knowledge-based system concept. An attempt has been made here to solve an old problem using newly developed information technology.

The development of an initial knowledge-based system for assisting highway and traffic engineers in the improvement and design of the roadside for safety has been discussed. It has been implemented as an interactive microcomputer tool. The user can query the user for its reasoning, and the system allows the user to selectively modify input values and quickly assess the impacts of such changes on the safety of the roadside configuration. This system was developed with two basic purposes: first, to show that the knowledge-based approach can be applied effectively to roadside safety and second to develop a knowledge-based system framework for the problem that could eventually develop into a full system. Once fully developed, this system is expected to support the traffic or highway engineer when making decisions about the location of roadside furniture. It does not, however, attempt to replace the highway or traffic engineer since his judgement will still be required. When viewed in this perspective, it becomes a very powerful tool for the assessment of a risk situation.

As research proceeded, it was realised that a multi-level system such as the one suggested by Hart could be built. Configuring fixed roadside objects is not easy. The decision will depend on many factors such as the nature and the type of object, the type of road, traffic volumes, posted speed limits etc. There is also the constraints imposed by the physical characteristics of each specific roadside i.e. the width of the right-of-way. In this case, judgement is required, and the rules will be heuristics. Once the heuristics are known, they can be implemented as an extra level. The construction of such a level will be easier than the one already implemented. However, determining the heuristics could be quite hard. The incorporation of accident severity should also be researched, to enable the decisions taken to be made based on risk, rather than just on probability.

VII. ACKNOWLEDGEMENTS

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Safety Barrier Systems in Germany
and Temporary Steel-Safety-Barriers (Latest Developments)

Bernd Wolfgang Wink
Economist
Volkmann & Rossbach GmbH & Co KG
Germany

(not attending the conference)
Safety Barrier Systems in Germany
and Temporary Steel-Safety-Barriers (Latest Developments)

Bernd Wolfgang Wink
Volkmann & Rossbach GmbH & Co KG
Germany

Abstract

Safety Barriers

a) Rigid and flexible Safety Barrier Systems - an approach to
determine Road and Traffic Safety by means of a priority-scale
for Safety

b) Safety barriers for permanent installation in Germany
(Test series, Videos, etc)

c) Safety Barriers for temporary installation
(New concepts, first tests and practical Experience-videos,
etc)
SAFETY BARRIER SYSTEMS IN GERMANY AND TEMPORARY STEEL-SAFETY-BARRIERS (LATEST DEVELOPMENTS)

Bernd Wolfgang Wink
Economist

Vonmann & Rossbach GmbH & Co. KG
Hohe Str. 11-19
D-5430 Montabaur
Federal Republic of Germany
Phone: 49/2602/1350
Fax: 49/2602/13549

The German Standard for permanent safety barriers was published in 1972, based on extensive tests conducted between 1962 and 1968. These tests already took into consideration the nowadays widely discussed deceleration values as an important factor for road safety.

The German Standard is a standard for a definitive system. Test results have shown that the Steel Guard Rails System is the most suitable one.

Everything of this system is completely defined and any change on the smallest detail is out of specification and unacceptable.

But do not be afraid of either the German inflexibility or of our lack of dynamic development, as you may infer from the statements above.

The German standard has been revised or amended several times since 1972.
Here there are some outstanding and decisive changes:

a) In 1980 was decided by the Federal Ministry that it is mandatory to install guard rails in central reserves of highways (Autobahnen), regardless their width. This decision was made as a result of critical accidents that took place on central reserve-sections being wider than 10 meters and had no guard rails.
Since this amendment, the accident-rate and the severity of the accidents in central reserve areas have been dramatically reduced.

b) Another amendment was the introduction of a post with rounded edges, called Sigma Post. This change of the standard has also resulted in a tremendous success, considering the reduction of the severity of the accidents involving two-wheels vehicles.
In August 1989, the German Standard was extensively revised. The traditional steel guard-rail system, however, was not at all changed as a permanent passive safety-device. The revision, which has been published under the name "R.P.S.", mainly affects the guidelines for installation, taking into account the recent variations of vehicles' weight, speed, and other components of public interest.

SAFETY BARRIERS IN HIGHWAY WORK ZONES

Safety in work zones, especially
- separation of driving lanes
- reduction of width of lanes
- control of traffic flow
- transition from permanent (normal) to temporary situations

was always dominated by products like

- road markings, including prefabricated foils
- road studs or cat's eyes
- plastic barriers or
- portable concrete barrier sections

But since the results of recent accident analysis show more and more that the numbers and severity of accidents in work zones are increasing dramatically, we have - as a steel guardrail manufacturer - decided to concentrate our efforts in Research and Development on new steel products and safety systems for work zones.

As "steel people" and hardliners for the flexible barrier systems, we are looking to find solutions on the basis of the safety parameters valid for flexible systems.
It is our aim to find the most adequate combination for

- flexible and safe reaction after impact
- tolerable displacement of the system upon impact
- smooth redirection of the vehicle after impact
- reducing the danger of vaulting the system, crashing into the oncoming traffic
- easy storage
- easy loading
- easy transportation
- easy erection
- easy repair and maintenance
- either no anchoring on the road or
- only anchorage at the beginning and end of the systems
- easy disassembly in case of emergency
- easy re-application after termination of the work zone
- easy transfer of the total system by special device in the work zone (e.g. changing from 2 to 3 lanes or vice versa)
- reasonable costs

Results of our first efforts in Research and Development are our systems

Vario Guard and Mini Guard

They have been carefully tested by the University of Zurich, Switzerland (Vario-Guard) and the BAST, Federal Research Institute in Germany (Mini-Guard).
Experience with their installation in Germany since last year is confirming our enthusiasm for these 2 systems, which may lead to a new successful era of steel barrier systems as outstanding safety devices for the protection of people and vehicles in work zones.

B.W. Wink
Side Impact Crash Testing of Highway Safety Hardware

John F Carney III
Professor of Civil Engineering
Associate Dean for Graduate Affairs
Vanderbilt University
U.S.A.

and

Malcolm H Ray
Research Instructor
Vanderbilt University
U.S.A.
Side Impact Crash Testing of Highway Safety Hardware

John F Carney III

and

Malcolm H. Ray

Department of Civil and Environmental Engineering
Vanderbilt University
Nashville
TN, USA

Abstract

Side impact involving vehicles and fixed roadside objects represent an extremely dangerous type of accident with and associated annual cost to society in the United States of more than three billion dollars. Side impacts with utility poles, trees, and other narrow objects account for 75 percent of all fatal fixed-roadside side impact accidents. The NHTSA and automobile manufacturers have recently expended a great deal of effort in formulating and studying the side impact problem. These studies have focused on vehicle-to-vehicle side impacts and the thoracic trauma which usually occurs in such collisions. In side impacts with narrow objects, however, the injury mechanism might be quite different. Full-scale crash tests of small cars and currently operational luminaire supports have shown that the occupant's head is often the first portion of the body to contact the vehicle interior. If the occupant and struck object are aligned, the occupant effectively strikes the pole directly causing extremely large impulses very early in the impact event. Even breakaway luminaire supports have a high probability of fatally injuring the occupant since the occupant strikes the pole long before the pole breaks away. Understanding of this important impact scenario is vital to making effective design changes to the pole and automobile. Installing interior padding, for example, without strengthening the door structure may have little beneficial effect for occupants of vehicles involved in side impacts with narrow objects.

This paper reports on a side impact crash testing program which the authors are conducting under contract with the Federal Highway Administration. The testing program is made up of three categories of crash tests:

- Demonstration Tests
- Impact Speed Sensitivity Tests
- Retrofit Design Tests

The Demonstration Tests demonstrate the performance characteristics of guardrail ends and various end treatments under side impact conditions. The system tests will include a Modified
Eccentric Loader, a Breakaway Cable Terminal (BCT), and a Narrow Connecticut Impact Attenuation System (NCIAS). The impact conditions for these tests (impact velocity = 30 mph, heading angle = 56 degrees, and yaw angle = 56 degrees) were chosen based on the 90 percentile values found in an accident data analysis of the 1980-1985 Fatal Accident Reporting System and the 1982-1985 National Accident Sampling system data bases.

The objective in conducting the Impact Speed Sensitivity Tests is to determine the effect of impact velocity on occupant risk for two different luminaire support concepts: the slip base pole design and the energy absorbing ESV pole designed in Sweden.

The Retrofit Design Tests evaluate a new activation hoop retrofit system for use with slip base luminaire supports. A 30-ft slip base support is tested under 20 and 30 mph side impact conditions with standard and reinforced door structures.

Non-tracking side impacts with roadside appurtenances are very hazardous crash events. This type of crash test is not currently conducted when hardware is being developed. The side impact crash testing program described in this paper will form the basis for establishing non-tracking, side impact test and evaluation criteria which could have a significant effect on the highway safety community’s ability to design safe and effective roadside hardware.
SIDE IMPACT CRASH TESTING OF HIGHWAY SAFETY HARDWARE
John F. Carney III
Professor of Civil Engineering and
Associate Dean for Graduate Affairs
Vanderbilt University

and
Malcolm H. Ray
Research Instructor
Vanderbilt University

1. INTRODUCTION - CHAPTER 1

In the United States, approximately 160,000 people are involved in single vehicle side impact accidents with fixed objects every year. One out of every three vehicle occupants connected with this type of accident is injured and approximately 1,600 yearly fatalities occur. It is estimated that the yearly societal costs of side impact accidents exceeds three billion dollars.

An investigation of accident data from both the National Accident Sampling System (NASS) and the Fatal Accident Reporting System (FARS) data bases reveals the various types of fixed objects struck in single-vehicle, side-impact passenger-car collisions, and this information is summarized in Table 1 [1]. The fixed objects are divided into three categories: narrow, broad, and other objects. Narrow objects accounted for almost 80% of the occupant fatalities though they comprise only 60% of the fixed-object accidents. Because narrow objects are involved in a greater percentage of fatal accidents than in accidents overall, these data suggest that narrow objects are more likely to cause a fatality when struck in an accident. Trees appear to be especially dangerous, as they are involved in only 25% of the fixed-object accidents, but are responsible for approximately 48% of the fatalities. The data shown in Table 1 indicate that the fatality rate for side impacts with trees is approximately 1.9 fatalities per 100 accidents. Utility poles also seem to be quite harmful since they account for 25% of the fatalities and only 21% of total accidents. Poles of all types are responsible for nearly one-third of all side-impact fixed-object fatalities. Like trees, the chance of being fatally injured in a collision with a utility pole is somewhat greater than 1 in 100.

Side impacts with trees and poles are a subset of the broader tree and utility-pole-accident problem. These same objects are known to be hazardous in frontal collisions. Any programs that address reduction of tree and utility pole collisions will automatically reduce the number and severity of side-impact fixed-object accidents.

Side-impact collisions with broad objects are not as likely to cause fatalities as are side impacts with narrow objects. Broad objects are involved in 18% of side-impact collisions, but account for only 12% of the fatalities. Guardrails are responsible for most of this difference, with 9% of NASS fixed-object collisions involving guardrails and only 4% causing fatalities. In comparison to the tree-collision fatality rate of 1.9, the side-impact-fatality rate for guardrail accidents is 0.4, five times less than the tree and utility-pole-fatality rate.
Table 1. Single-vehicle side-impact passenger-car collisions where most harmful event was fixed roadside object.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency</td>
<td>Percent</td>
<td>Frequency</td>
</tr>
<tr>
<td>Narrow Objects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tree</td>
<td>784</td>
<td>47.6</td>
<td>19,865</td>
</tr>
<tr>
<td>Utility pole</td>
<td>434</td>
<td>26.3</td>
<td>18,593</td>
</tr>
<tr>
<td>Other post/pole</td>
<td>39</td>
<td>2.3</td>
<td>1,365</td>
</tr>
<tr>
<td>Light support</td>
<td>45</td>
<td>2.7</td>
<td>3,072</td>
</tr>
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<td>Sign support</td>
<td>12</td>
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<td>Mailbox</td>
<td>—</td>
<td>—</td>
<td>311</td>
</tr>
<tr>
<td>Delineator post</td>
<td>—</td>
<td>—</td>
<td>142</td>
</tr>
<tr>
<td>Fire hydrant</td>
<td>1</td>
<td>0.1</td>
<td>—</td>
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<tr>
<td>Total narrow objects</td>
<td>1,315</td>
<td>79.9</td>
<td>45,283</td>
</tr>
<tr>
<td>Broad Objects</td>
<td></td>
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<tr>
<td>Guardrail</td>
<td>70</td>
<td>4.3</td>
<td>3,445</td>
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<td>Bridge pier/abutment</td>
<td>44</td>
<td>2.7</td>
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<tr>
<td>Fence</td>
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<td>Wall</td>
<td>18</td>
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<td>580</td>
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<td>Bridge parapet</td>
<td>24</td>
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<tr>
<td>Concrete barrier</td>
<td>4</td>
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</tr>
<tr>
<td>Other longitudinal barrier</td>
<td>2</td>
<td>0.1</td>
<td>270</td>
</tr>
<tr>
<td>Impact attenuator</td>
<td>1</td>
<td>0.1</td>
<td>210</td>
</tr>
<tr>
<td>Total broad objects</td>
<td>189</td>
<td>11.5</td>
<td>6,850</td>
</tr>
<tr>
<td>Other Object Types</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ditch</td>
<td>15</td>
<td>0.9</td>
<td>2,962</td>
</tr>
<tr>
<td>Other fixed object</td>
<td>30</td>
<td>1.8</td>
<td>1,942</td>
</tr>
<tr>
<td>Culvert</td>
<td>39</td>
<td>1.8</td>
<td>450</td>
</tr>
<tr>
<td>Building</td>
<td>25</td>
<td>1.5</td>
<td>384</td>
</tr>
<tr>
<td>Unknown embankment</td>
<td>22</td>
<td>1.3</td>
<td>—</td>
</tr>
<tr>
<td>Earth embankment</td>
<td>12</td>
<td>0.8</td>
<td>2,480</td>
</tr>
<tr>
<td>Curb</td>
<td>2</td>
<td>0.1</td>
<td>386</td>
</tr>
<tr>
<td>Rock embankment</td>
<td>6</td>
<td>0.4</td>
<td>706</td>
</tr>
<tr>
<td>Shrubbery</td>
<td>1</td>
<td>0.1</td>
<td>—</td>
</tr>
<tr>
<td>Total other objects</td>
<td>143</td>
<td>8.6</td>
<td>9,510</td>
</tr>
<tr>
<td>Total of all objects</td>
<td>1,647</td>
<td>100.0</td>
<td>61,643</td>
</tr>
</tbody>
</table>

1.1 Current Crash Testing Standards

Both the current testing procedures contained in *NCHRP Report 230* [2] and the proposed new guidelines [3] recommend impact conditions only with tracking, unbraked vehicles. Side impact collisions have little to do with these highly idealized test conditions. The recognition of the importance of addressing this ongoing side impact issue resulted in the funding of a research effort by the Federal Highway Administration. An important phase of this ongoing side impact investigation is the full-scale side-impact crash testing program described herein.

1.2 The Early Crash Testing Program

A side impact crash testing program was conducted at the Federal Outdoor Impact Laboratory (FOIL) in 1987-88. The objective of that program was to investigate the impact response of light automobiles during low-speed broadside collisions.
with breakaway luminaire supports. The test matrix employed is shown in Table 2, the slipbase and transformer base luminaire support characteristics are presented in Table 3, and the test results are summarized in Table 4 [4].

It is of interest to note that breakaway did not occur in the only transformer base tested and in one of the slipbase tests. The resulting localized vehicle deformations and occupant risk values are quite high. The traditional occupant risk criteria, composed of calculated values of hypothetical occupant impact velocities and ride-down decelerations, are not adequate measures of injury potential in narrow-object side-impact crashes of this type because of the extensive deformations which take place in the passenger compartment structure. Nevertheless, these parameters provide a measure of the relative severities of the different tests. Similarly, the Head Injury Criteria (HIC) data is clouded by the fact that the side impact dummy employed in these tests was fitted with a Part 572 dummy head which was designed to represent the human head in frontal impacts. The lateral response of the head is probably stiffer than the frontal direction so it is reasonable to assume that the lateral HICs recorded would in general be higher than the equivalent frontal HICs. However, most of the HIC values are far in excess of the acceptable limiting value of 1000, and there is no doubt that severe head loadings existed.

2. THE 1991 SIDE IMPACT CRASH TESTING PROGRAM - CHAPTER 2

The tests described in Table 4 involved impact speeds of approximately 30 mph and slipbase luminaire supports which had performed well under frontal impact conditions. In order to better characterize the relationships between the various occupant risk parameters and occupant compartment intrusion, it was necessary to conduct additional crash tests with luminaire supports at lower and higher impact speeds. The luminaire supports selected for these new crash tests included the slipbase pole employed in the early test program and an energy dissipating pole developed in Sweden. The slipbase pole is designed so that an errant vehicle can pass by with little change in velocity after activating the slip mechanism.

The Swedish (ESV) pole uses a completely different principle to achieve the desired result: minimizing risk to the occupant. This device was developed during the late 1970's and is intended to stop a vehicle rather than let it pass. The collapse mechanism has been designed so that the occupant response in a frontal collision is well below the threshold of serious injury. In over a decade of use throughout Scandanavia there have been no fatalities reported in accidents involving ESV-like poles. By changing the dimensions of pole the energy dissipation can be optimized for different vehicle masses and speeds. Figure 1 shows the design features of the ESV pole. The outside of the pole is a hexagon formed from 0.053-inch thick steel sheet. Four 3/8-inch diameter round steel rods are tack welded to the inside of the skin. The four rods are butt-welded to 1-inch diameter anchor rods. The pole can be installed using either a soil mounted anchor or by directly attaching it to a rigid base. The test pole was fixed to the universal support at the FOIL. This support is a 2-inch thick steel plate. The poles that were delivered were for soil mounted applications so that anchor rods were shortened to allow them to be attached to the universal support. Rigid, deck-mounted supports similar to the ones used in this test are common in Scandanavia. In a collision, the tack welds fracture and the cross-section flattens. The flattened section is then pulled around the bumper or
Table 2. Test matrix for side impact test series.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Angle</th>
<th>Impact Location</th>
<th>Test Article</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>Slipbase</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>0</td>
<td>Transformer base</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>0</td>
<td>Slipbase</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>0</td>
<td>Slipbase</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>-12 in (near B-pillar)</td>
<td>Slipbase</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
<td>+12 in (near door center)</td>
<td>Slipbase</td>
</tr>
<tr>
<td>7</td>
<td>90</td>
<td>+24 in (near A-pillar)</td>
<td>Slipbase</td>
</tr>
<tr>
<td>8</td>
<td>90</td>
<td>0</td>
<td>Slipbase</td>
</tr>
</tbody>
</table>

90 = Broadside on Driver’s Door
0 = Centered on Occupant
+ = Forward of Occupant
- = Rearward of Occupant

1 in = 25.4 mm

Table 3. Properties of test base & pole.

<table>
<thead>
<tr>
<th>Type</th>
<th>Slipbase</th>
<th>Transformer Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Steel</td>
<td>Steel</td>
</tr>
<tr>
<td>Weight</td>
<td>416 lb</td>
<td>386 lb</td>
</tr>
<tr>
<td>Height, c.g.:</td>
<td>21 ft</td>
<td>23 ft, 10 in</td>
</tr>
<tr>
<td>Top diameter</td>
<td>3.5 in</td>
<td>6 in</td>
</tr>
<tr>
<td>Bottom diameter</td>
<td>7.5 in</td>
<td>8 in</td>
</tr>
<tr>
<td>Mast Arm Length:</td>
<td>15 ft, 9 in</td>
<td>14 ft, 9 in</td>
</tr>
<tr>
<td>Luminaire Height:</td>
<td>35 ft, 10 in</td>
<td>39 ft</td>
</tr>
<tr>
<td>Luminaire Weight:</td>
<td>51 lb</td>
<td>51 lb</td>
</tr>
<tr>
<td>Base Type:</td>
<td>California Type 31 slipbase</td>
<td>Transformer slipbase</td>
</tr>
<tr>
<td>Number of bolts:</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Size:</td>
<td>1 in diameter</td>
<td>1 in diameter</td>
</tr>
<tr>
<td>Type:</td>
<td>Instrumented to measure bolt load</td>
<td>Galvanized studs</td>
</tr>
<tr>
<td>Bolt Clamp Load:</td>
<td>14 kips tension (tests 1,3,4,5,6,7,)</td>
<td>200 ft-lb (test 2)</td>
</tr>
<tr>
<td></td>
<td>0 kips tension (test 8)</td>
<td></td>
</tr>
</tbody>
</table>

1 lb = 0.454 kg
1 in = 25.4 mm
1 ft = 0.305 m

sill, continuously flattening the cross-section. Energy is absorbed by the flattening and wrapping of the pole around the vehicle.

The luminaire crash test matrix and test results are summarized in Table 5. A total of 4 ESV and 3 slipbase pole tests were conducted. Impact speeds ranged from 17.8 to 41.5 mph, and the impact point was aligned on the shoulder of the dummy.
Table 4. Test Results.

<table>
<thead>
<tr>
<th>TEST NUMBER</th>
<th>SI#1</th>
<th>SI#2</th>
<th>SI#3</th>
<th>SI#4</th>
<th>SI#5</th>
<th>SI#6</th>
<th>SI#7</th>
<th>SI#8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Plymouth</td>
<td>Dodge</td>
<td>Dodge</td>
<td>Plymouth</td>
<td>Plymouth</td>
<td>Plymouth</td>
<td>Dodge</td>
<td>Plymouth</td>
</tr>
<tr>
<td>Model</td>
<td>Champ</td>
<td>Colt</td>
<td>Colt</td>
<td>Champ</td>
<td>Champ</td>
<td>Champ</td>
<td>Colt</td>
<td>Champ</td>
</tr>
<tr>
<td>WeightI (lb)</td>
<td>1849</td>
<td>1850</td>
<td>1847</td>
<td>1850</td>
<td>1850</td>
<td>1850</td>
<td>1847</td>
<td>1848</td>
</tr>
<tr>
<td>Impact speed (mi/h)</td>
<td>29.4</td>
<td>28.6</td>
<td>30.5</td>
<td>30.5</td>
<td>29.7</td>
<td>28.3</td>
<td>28.9</td>
<td>29.6</td>
</tr>
<tr>
<td>Speed change (mi/h)</td>
<td>6.1</td>
<td>6.1</td>
<td>4.1</td>
<td>6.1</td>
<td>8.4</td>
<td>28.3</td>
<td>10.2</td>
<td>4.9</td>
</tr>
<tr>
<td>Occupant impact velocity (ft/s)</td>
<td>9.7</td>
<td>26.7</td>
<td>6.1</td>
<td>9.1</td>
<td>11.4</td>
<td>28.8</td>
<td>14.7</td>
<td>7.1</td>
</tr>
<tr>
<td>Ridedown acceleration (g)</td>
<td>1.5</td>
<td>8.4</td>
<td>2.3</td>
<td>1.5</td>
<td>3.1</td>
<td>4.9</td>
<td>3.5</td>
<td>2.0</td>
</tr>
<tr>
<td>HIC</td>
<td>1593</td>
<td>3385</td>
<td>8684</td>
<td>8026</td>
<td>64</td>
<td>2191</td>
<td>150</td>
<td>1996</td>
</tr>
<tr>
<td>Maximum vehicle crush (in)</td>
<td>10.0</td>
<td>26.0</td>
<td>9.5</td>
<td>10.0</td>
<td>13.0</td>
<td>36.0</td>
<td>7.7</td>
<td>7.5</td>
</tr>
</tbody>
</table>
The individual crash tests are described below.

Test 1 - ESV Pole / 1982 Colt

The impact occurred at 29.9 mph at a point on the left door in line with the shoulder of the occupant, 28 inches behind the longitudinal location of the center of gravity of the vehicle measured without the dummy in the vehicle. Upon impact the vehicle’s driver side door began to crush and the pole started to collapse. Just prior to impact, the dummy was slightly out of position, leaning in-board. The actual flail distance at impact was 6.5 inches. After impact the dummy rapidly accelerated toward the door, striking the window and the intruding pole. As the impact event progressed the vehicle began to yaw counter-clockwise, continued forward away from the impact point after yawing a total of 93 degrees. Its final resting position was approximately 5 feet to the right and 12 feet downstream of the impact point. The vehicle had a maximum roll angle of 6.8 degrees as it leaned toward the test pole due to the side sliding forces acting on the tires.

The vehicle was extensively damaged during the collision. The maximum residual crush of the vehicle at the impact point was 16 inches. Photographs of the vehicle and the pole before and after the collision event are shown in Figure 2. The vehicle was bent about the impact point with the wheel base shortened almost 6 inches on the impact side.
Table 5. 1991 Crash Test Results.

<table>
<thead>
<tr>
<th>Test</th>
<th>Date</th>
<th>(mi/hr) Impact Speed</th>
<th>(degrees) Yaw Angle</th>
<th>Device</th>
<th>Vehicle</th>
<th>Impact Point</th>
<th>(lb) Gross Vehicle Weight</th>
<th>(ft/s) 12-in flail Occupant Impact Velocity</th>
<th>(g) Ridedown Acceleration</th>
<th>HIC</th>
<th>TTI</th>
<th>(in) Maximum Vehicle Crush</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-10-91</td>
<td>29.9</td>
<td>90</td>
<td>ESV Pole</td>
<td>Colt</td>
<td>on shoulder</td>
<td>2,015</td>
<td>13.38</td>
<td>5.47</td>
<td>398</td>
<td>145</td>
<td>16.0</td>
</tr>
<tr>
<td>2</td>
<td>1-18-91</td>
<td>17.8</td>
<td>90</td>
<td>ESV Pole</td>
<td>Colt</td>
<td>on shoulder</td>
<td>2,015</td>
<td>14.00</td>
<td>3.45</td>
<td>44,101</td>
<td>47</td>
<td>9.0</td>
</tr>
<tr>
<td>3</td>
<td>1-25-91</td>
<td>29.9</td>
<td>90</td>
<td>ESV Pole</td>
<td>Honda</td>
<td>on shoulder</td>
<td>2,015</td>
<td>8.41</td>
<td>7.13</td>
<td>503</td>
<td>97</td>
<td>8.5</td>
</tr>
<tr>
<td>4</td>
<td>2-11-91</td>
<td>18.9</td>
<td>90</td>
<td>Slipbase Pole</td>
<td>Colt</td>
<td>on shoulder</td>
<td>2,015</td>
<td>23.75</td>
<td>12.13</td>
<td>2,513</td>
<td>82</td>
<td>18.8</td>
</tr>
<tr>
<td>5</td>
<td>2-14-91</td>
<td>41.5</td>
<td>90</td>
<td>ESV Pole</td>
<td>Colt</td>
<td>on shoulder</td>
<td>2,015</td>
<td>17.63</td>
<td>10.43</td>
<td>139</td>
<td>109</td>
<td>10.0</td>
</tr>
<tr>
<td>6</td>
<td>2-21-91</td>
<td>20.8</td>
<td>90</td>
<td>Slipbase Pole</td>
<td>Colt</td>
<td>on shoulder</td>
<td>2,015</td>
<td>13.29</td>
<td>5.27</td>
<td>—</td>
<td>—</td>
<td>10.0</td>
</tr>
<tr>
<td>7</td>
<td>2-28-91</td>
<td>39.8</td>
<td>90</td>
<td>Slipbase Pole</td>
<td>Colt</td>
<td>on shoulder</td>
<td>2,015</td>
<td>11.11</td>
<td>10.85</td>
<td>17,776</td>
<td>413</td>
<td>13.0</td>
</tr>
</tbody>
</table>
The pole was also extensively damaged. On impact the pole activated and began to wrap around the sill and door structure. Approximately 4 ft of the pole was flattened and had been pulled over the sill. As the impact event progressed the inertia of the pole caused a buckle to form about 15 ft up the pole. The base of the pole remained intact and did not fracture. One of the butt-welded connections between the 3/8-inch rods and the 1-inch anchor bolts did, however, fracture. The galvanized sheet around the base was also torn in several places. Overall the device performed in a manner consistent with its design.

The occupant impact velocity and ridedown deceleration value in this test were both below NCHRP Report 230 limits. In addition, the HIC was quite low, and the vehicle response was stable. However, the Thoracic Injury Index (TTI) value was unacceptably high.

Figure 2. Test 1 Response (ESV, 29.9 mph).
Test 2 - ESV Pole / 1983 Colt

This test was identical to the first test except that the impact speed was reduced to 17.8 mph. The dynamic responses of the dummy, striking vehicle, and ESV pole, however, were markedly different from those of Test 1. While the dummy in Test 1 was essentially upright at the instant of impact, the Test 2 dummy's head was resting against the side window of the vehicle. The ensuing direct impact from the pole to the head drove glass fragments into the skull area, and the resulting HIC value of 44,101 was far in excess of the allowable limiting value of 1000. On the other hand, the TTI value was a low 47 g's. The strikingly different HIC and TTI values for Tests 1 and 2 illustrate the critical importance of occupant location at impact. In the higher speed first test, the 6.5 in. dummy flail distance traversal was preceded by the door structure deformation process, thereby reducing the occupant impact velocity with both the pole and the vehicle interior. In the lower speed second test, however, the head of the dummy was subjected to the maximum possible impact loading in the event — direct contact with the pole at an impact speed equal to that of the vehicle. Because of the low impact speed, much less deformation occurred in the ESV pole than in the first test, and the vehicle was less extensively damaged, as seen in Figure 3.

![Figure 3. Test 2 Response (ESV, 17.8 mph)](image)

Test 3 - ESV Pole / 1984 Honda Civic

The door structure of the Honda Civic employed was stronger and stiffer than those of the Dodge Colts used in the first two tests. The purpose of Test 3 was to investigate the effect of this new door structure on the impact response of the dummy, vehicle, and pole for a 30 mph impact. The actual impact speed was 29.9 mph. Unfortunately, the ESV pole in this test was defective, and fracture occurred at its base. The pole fracture surface and deformed door structure of the vehicle are illustrated in Figure 4. Because of the fracture failure, it is inappropriate to directly compare the results of this test to those of Tests 1 and 2. It is of interest to note, however, that the head of the dummy was only subjected to a glancing blow from the pole and both the HIC and TTI values for this test were within allowable limits.
Test 4 - Slipbase Luminaire Support / 1984 Colt

The earlier FOIL side impact tests summarized in Table 4 were conducted at a nominal impact speed of 30 mph. In Test 4, the same slipbase used in these tests (see Table 4) was retested with the same 14 kip bolt clamping load but at a lower impact speed 18.9 mph. This combination of high clamping force and low impact speed resulted in system lockup. The slipbase mechanism did not release and the resulting damage to the side structure of the automobile, shown in Figure 5, is quite extensive.

The TTI for this test was an acceptable 82 g's, but the calculated HIC value of 2513 is two and a half times the acceptable upper limit. As occurred in Test 2, the
head of the dummy was resting against the side window of the automobile when
the side impact occurred. The result was a possibly fatal injury at this low 18.9
mph impact speed.

Figure 5. Test 4 Response (Slipbase, 18.9 mph)

Test 5 - ESV Pole / 1983 Colt
The vehicular impact velocity in this test was 41.5 mph, and the performance of
the ESV pole under this severe impact condition was excellent. In fact, a com-
parison of HIC, TTI, and vehicle crush values for this test with the corresponding
results from the 29.9 mph ESV test (see Table 5, Tests 1 and 5) shows that the high
speed occupant risk measures are significantly smaller in all three cases (HIC: 139
vs 398; TTI: 109 vs. 145; vehicle crush 10 inches vs. 16 inches). This anomalous result occurred because the ESV pole responded like a crash cushion under the high speed impact condition. An extensive amount of kinetic energy was dissipated as approximately 2/3 of this pole length collapsed during the impact event. The vehicle was brought to a controlled stop just behind the pole, as seen in Figure 6. It is of interest to note that, in both Tests 1 and 5, the dummy was essentially upright when the initial impact occurred.

Figure 6. Test 5 Response (ESV, 41.5 mph)

Test 6 - Slipbase Luminaire Support / 1982 Colt
This test is a repeat of Test 4 except that the bolt clamping force was reduced from 14 to 6 kips. Unlike the Test 4 case, lockup did not occur. Damage to the side structure of the vehicle was less severe. The maximum crush was 10 inches in this test, compared with 18.8 inches of crush in the lockup test (Test 4). The comparable ESV pole test (Test 2) resulted in a vehicular crush of 9.0 inches. The HIC and TTI values were not obtainable in this test due to failure of the dummy instrumentation.
Test 7 - Slipbase Luminaire Support / 1985 Colt

The impact speed in this final test was 39.8 mph and, therefore, is comparable to the 41.5 mph ESV pole test (Test 5). The bolt tension for this test was 14 kips, and the slipbase released with little associated vehicular velocity change and extensive vehicular travel after impact. Although the slipbase pole performed as designed, the resulting occupant risk parameters (see Table 4) were very high compared to those of the comparable ESV pole test. For example, the slipbase HIC value was 17,776 while the ESV HIC was 139. The slipbase TTI value was 413 compared to the ESV value of 109. Finally, the crush of the side structure was 3 inches more in the Test 7 vehicle. It is highly probable that a fatal injury would result from the impact conditions of Test 7.
3. DISCUSSION AND CONCLUSIONS - CHAPTER 3

Side impacts involving vehicles and fixed roadside objects represent an extremely dangerous and costly type of accident. Side impacts with utility poles, trees, and other narrow objects account for 75 percent of all fatal fixed-roadside side impact accidents. The NHTSA and automobile manufacturers have recently expended a great deal of effort in formulating and studying the side impact problem. These studies have focused on vehicle-to-vehicle side impacts and the thoracic trauma which usually occurs in such collisions. In side impacts with narrow objects, however, the important injury mechanisms can be quite different. The full-scale crash test program described in this paper shows that the occupant’s head is often the first portion of the body to contact the vehicle interior. If the occupant and struck object are aligned, the occupant effectively strikes the pole directly causing extremely large impulses very early in the impact event. Even breakaway luminaire supports have a high probability of fatally injuring the occupant since the occupant strikes the pole long before the pole breaks away. An understanding of this important impact scenario is vital to making effective design changes to the pole and automobile. Installing interior padding, for example, without strengthening the door structure may have little beneficial effect for occupants of vehicles involved in side impacts with narrow objects.

One fact that is clearly illustrated by the 1991 test results reported herein is that the NCHRP Report 230 flail space occupant risk procedures yield little of value for this type of crash scenario. In all seven tests, the occupant impact velocities and ridedown accelerations calculated were well below the recommended design values of 30 fps and 15 g, respectively. The unacceptably high HIC and TTI values obtained, however, indicate that a severe or fatal injury would have resulted in most of the seven test cases. A notable exception to this trend was the excellent performance of the ESV pole under an impact condition of 41.5 mph (Test 5).

Although non-tracking side impacts with roadside appurtenances are very hazardous crash events, this type of crash test is not currently conducted when hardware is being developed. The side impact crash testing program described in this paper could form the basis for establishing non-tracking, side impact test and evaluation criteria which could have a significant effect on the highway safety community’s ability to design safe and effective roadside hardware.

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Safety Assessment of Highway Designs

Malcolm H Ray
Director, Engineering Services
Momentum Engineering
USA

and

Lori A Troxel
Research Assistant
Vanderbilt University
USA
Safety Assessment of Highway Designs

Malcolm H. Ray
Director, Engineering Services
Momentum Engineering
1103 Dickinson Lane
Franklin, Tennessee 37064

Lori A. Troxel
Research Assistant
Department of Civil and Environmental Engineering
Vanderbilt University
Nashville, Tennessee 36235

Introduction

Safety has been an important aspect of roadway design for more than 30 years. Unlike other parts of the design process, however, it is difficult to quantify safety so it is usually treated in an unsystematic, ad hoc way. There are potential safety tradeoffs in design that are usually not addressed: Would it be safer to pave a narrow shoulder or widen an unpaved shoulder? Would moving a utility pole back another 10 feet from the edge of shoulder be safer than putting a guardrail in front of it? How much would safety be improved? Will the improvement be worthwhile? These questions are, at present, difficult to answer because there is no systematic way of quantifying safety.

The focus of highway design has shifted in the past decade from the design of new roadways to the redesign of existing, often substandard roadways. Often roadways that were considered adequate under the traffic conditions of 30 years ago are operating under much more demanding conditions today. One of the primary purposes for redesigning a roadway segment is to improve safety. In the United States, the Federal Highway Administration (FWHA) plans to require all states to implement safety management plans within the next several years. The primary objectives of a safety management plan are to identify and prioritize hazardous roadway locations and features [1]. Although these objectives are easily stated they are difficult to achieve because there is no commonly accepted technique for quantifying safety. This paper will describe a systematic technique for quantifying safety that can be used to identify, prioritize and compare hazardous locations.

Safety management should provide a way to prioritize needs and allocate funds.
Since there will always be more deserving improvement projects than there are funds to implement them, it is crucial to have some method of rationally and systematically choosing projects to fund. Analysis of a state's accident records, for example, may indicate that serious accidents appear to occur at certain locations more than others. The state personnel may assemble a list of such locations for consideration as possible improvement projects. That there are problems at these locations is obvious since they have experienced high concentrations of accidents. The engineer must decide if these accidents are related to some correctable roadway feature and then use some technique to decide which projects should have the highest priority. The top priority should be a function of the characteristics of the site as well as the operating conditions of the roadway. A very unsafe road segment with low traffic volume may not pose as pressing a need as a safer, though deficient, road segment that experiences higher traffic and higher speeds. Currently engineers use their judgement, rules-of-thumb or cost effectiveness analysis to prioritize improvement projects. The subject of this paper is a more systematic technique that can be used to quantify the level of safety of a particular roadway. An object oriented software technique for implementing this technique is then described in later sections of this paper.

Quantifying Safety

Safety and risk are complementary properties: if the risk of traversing a particular road segment can be defined, the safety of the segment can also be defined. One early and persistent measure of risk is the number of injury accidents that occur in a given period, often one year [2]. Glennon suggested the following widely used conceptual model:

\[
E(I) = V \cdot P(E) \cdot P(A|E) \cdot P(I|A)
\]  

where,

\[
\begin{align*}
E(I) &= \text{Expected number of injury accidents per year}, \\
V &= \text{Traffic volume in vehicles per year}, \\
P(E) &= \text{Probability of a vehicle encroachment while traversing the hazard}, \\
P(A|E) &= \text{Probability of an accident given an encroachment has occurred, and} \\
P(I|A) &= \text{Probability of an injury accident given that an accident has occurred.}
\end{align*}
\]

Equation 1 estimates the number of injury accidents for a particular feature of a roadway. For example, a utility pole could be expected to be involved in a certain number of injury accidents each year. Estimating the safety of a road segment would involve summing up the effects of all the potentially hazardous events a vehicle occupant would encounter. Estimating the expected number of injury accidents for a feature would involve estimating the three probabilities for each type of hazard along the roadway. This conceptual model has been widely used, especially in the area of roadside design, and has formed the basis for much of the work using cost effectiveness methods.
One reason for using the three conditional probabilities in equation 1 is that certain roadway characteristics affect one probability but not another. If off-road fixed object collisions are considered, the lane width, travel speed and horizontal curvature of the roadway are characteristics that affect the probability of a vehicle leaving the roadway, $P(E)$ but do not necessarily affect the probability of an accident occurring given that an encroachment has occurred, $P(A|E)$. Likewise, the distance from the traveled way does not effect the probability that a vehicle will leave the road ($P(E)$) but it does effect the probability that an encroachment will become an accident ($P(A|E)$). The formulation of equation 1, then, provides a way of segregating roadway and roadside characteristics into physically meaningful groups. A particular characteristic might belong to several groups if it has an effect on several probabilities. Speed, for example, would be useful in predicting the probability of encroachment ($P(E)$) as well as predicting the probability of injury accident ($P(I|A)$). The characteristics that belong to each of these groups could be determined either subjectively or statistically using classification analysis [3] [4] [5].

The expected number of injury accidents on a road segment could be estimated by combining the effects of each hazard in the segment. If safety is defined as the probability of not being involved in an injury accident, the safety index, $S$, could be defined as:

$$S = \sum_{i=1}^{n} P_i(T) = \sum_{i=1}^{n} \{1 - P_i(E) \cdot P_i(A|E) \cdot P_i(I|A)\}$$

(2)

where the subscript $i$ denotes a particular scenario like running off the road and striking a tree or encroaching on another lane and side-swiping another vehicle. Equation 2 makes the implicit assumption that hazardous events are mutually exclusive which is not strictly true. If the hazards are defined as first harmful events this problem is reduced greatly. If a driver experiences a first harmful event in a head-on vehicle-to-vehicle collision any subsequent collisions by definition would not be a first harmful event. If the vehicle is involved in one accident sequence and then drives away and is involved in another separate accident the mutual exclusion assumption would be violated. This situation is probably a very rare occurrence so it has been neglected. The disadvantage to counting first rather than most harmful events is that the collision that causes the most injury in an accident is often experienced in a subsequent event. In collisions with guardrails it has been shown that for redirectional accidents the most serious collision is almost always not the guardrail collision but a subsequent event like striking another vehicle or another roadside object after being redirected [6] [7] [8]. The first harmful event is the event that precipitates the remaining accident sequence. Use of the first harmful event is therefore appropriate though it must be remembered that the severity values refer to the entire accident sequence not just the first harmful event. The safety index in equation 2 represents the combination of the effects of all the accident scenarios along the roadway.
Encroachment Rate

The quantity $VP(E)$ in equation 1 is often referred to as the encroachment rate. It is an estimate of the number of vehicles that leave the roadway in a given period. The concept of encroachment has been used extensively for run-off-road accidents but it can be generalized to include encroachments into other lanes or encroachment into the safe gap between vehicles. Encroachments initiate a sequence of events that sometimes results in an accident: roadside encroachments for run-off-road accidents, lane encroachments for side-swiping and head-on vehicle-to-vehicle accidents, and vehicle gap encroachment for rear-end accidents.

One common model used for encroachments is a simple linear model that uses the assumption that encroachments are linearly related to the average daily traffic (ADT) [9]. This model has been used in several computer programs used for cost estimation[10] [11]. Although traffic volume should be an important component of any encroachment model the linear model has several deficiencies. First, the rate of encroachment should increase from zero with increasing volume but when the volume exceeds the highest service level traffic should slow or stop and encroachments should again be very unlikely. Other important effects are not a function of ADT. Encroachments should be greater on roads with more curves and grades than on straight level roads. Roads with narrow lanes and shoulders should have more encroachments than roads with wider lanes and shoulders. The encroachment rate, then, should be a function of a number of roadway characteristics. The following expression could be used to represent a general model for the probability of a vehicle encroaching:

$$P_j(E) = \prod_{i=1}^{n} a_i x_i^{b_i}$$

(3)

The $x_i$ are independent variables, the $a_i$ are coefficients, and the $b_i$ are exponents. These values could come from statistical analyses or from experience. The important idea is that the encroachment is predicted by some set of measurable characteristics of the highway.

Zegeer has presented the following regression model that estimates the number of accidents on a road segment [12]:

$$E(A) = 0.0019ADT^{0.88}0.8786W_L0.9192W_p0.9316W_{up}1.2365H0.882T_11.3221T_2$$

(4)

where

- $E(A)$ = Expected number of accidents per mile per year,
- $ADT$ = Average daily traffic,
- $W_L$ = Lane width,
- $W_p$ = Paved shoulder width,
- $W_{up}$ = Unpaved shoulder width,
- $H$ = Hazard index,
- $T_1$ = Level terrain indicator, and
- $T_2$ = Hilly terrain indicator.
Equation 4 is not an encroachment model *per se* since it predicts accidents rather than encroachments, but it does have some of the properties required of a general purpose encroachment model. Although this expression also increases monotonically with traffic volume like the linear model, the *rate* decreases with increasing volume. The other more interesting aspect of Zegeer’s model is that other roadway features are included. A general encroachment model should have the ability to include not only traffic volume effects but other characteristics of the roadway.

### Accident Frequency

The term $P(A|E)$ in equation 1 represents the probability that an encroachment will become an accident. Often the drivers of encroaching vehicles can regain control before actually striking a hazardous object, pedestrian or other vehicle. Other times a collision does occur but is not reported to the police presumably because the resulting accident was relatively minor. The term $P(A|E)$, then, is the probability that an encroachment becomes a police reported accident. Unfortunately this is a very difficult quantity to estimate since unreported accidents are generally not included in typical accident data bases.

The distance from the edge of the roadway to a hazardous roadside object has been shown by several authors to be a very important factor in predicting whether an encroachment progresses into an accident [13] [14]. Glennon investigated several mathematical models for predicting the probability of an encroachment progressing into an accident. The model he selected was an exponential model. This model fit the statistical data as well as other trigonometric models but it also has features that make it intuitively appealing. An exponential model predicts that the greatest probability of striking an off road object occurs when the object is at the edge of pavement. The probability decreases to zero at an offset distance of infinity so the farther away the object is the less likely a collision with a vehicle becomes. The exponential model is given by the following expression:

$$P(A|E) = e^{-0.08224y} \tag{5}$$

where $y$ is the lateral distance from the edge of pavement to the hazard. This model makes good intuitive sense since it implies that the probability of striking a hazardous object is greatest when it is located at the pavement edge and decreases as the distance to the object increases.

The probability that an encroachment will be transformed into an accident, then, is a function of the characteristics of a road segment. The following general purpose model, which is similar to equation 3, could be used to estimate this conditional probability:

$$P_j(A|E) = \prod_{i=1}^{n} c_i y_i^{d_i} \tag{6}$$

where $y_i$ are independent variables, the $c_i$ are coefficients, and the $d_i$ are exponents. These quantities should be characteristics of the roadside geometry and the position of the hazard. For example, while the lane width might affect the probability of leaving the road, it does not affect the probability of striking an
object. Likewise, the offset distance to a utility pole does not affect the probability of leaving the road but it does effect the probability of an encroachment becoming an accident.

**Severity Indices**

The conditional probability $P(I|A)$ is often called the severity index. It represents the likelihood of sustaining a serious injury given that an accident has occurred. The actual severity of a particular accident is a function of the characteristics of the particular collision and the object struck. The severity of a guardrail collision may be a function of impact speed, impact angle, appurtenance strength and the after-collision trajectory. The severity of a rollover on a steep side slope might be a function of the vehicle track width, the slope, the road grade, and the embankment height. Although the variables that could be used to predict injury are different for different accident types, there is some set of variables that affect the probability of sustaining a serious injury. A general expression for the probability of an accident becoming a serious injury accident could be expressed as:

$$\Pr(I|A) = \prod_{i=1}^{n} e_i z_i^{f_i}$$

(7)

where the $e_i$ are coefficients, the $z_i$ are independent variables, the $f_i$ are exponents and $\Pr_j(I|A)$ is the probability of sustaining an injury in accident scenario $j$. The members of the terms included in the severity model should be observable characteristics of the hazard. The coefficients, variables and exponents needed in the model can be found by a variety of statistical methods including linear and nonlinear regression analyses, the method of least squares and cluster analysis. The use of these methods, however, does not necessarily require the use of accident data. In general there will be many accident scenarios where detailed data in large enough quantities are not available. In these cases models could be derived from testing (i.e. full-scale crash testing or vehicle stability testing), computer simulations, research community consensus or, in the absence of anything else, policy decisions. A mixture of these methods could also be used.

The above sections have described general purpose models that can be used to model the three required probabilities in equation 1. Finding the particular characteristics and values in these models will require a significant long term effort which is not the focus of this paper. The objective of the above discussion is to illustrate that general models can be defined that have physical meaning. The particulars of the models will undoubtedly change as better data and analyses refine the current understanding of the effect of roadside features on safety.

**Software Technique**

If models like those discussed in the previous sections were available the safety of a particular road segment could be estimated by adding up the combined effects
of each potential hazard along the road segment. Unfortunately, this analysis would require a great deal of information about the geometrics and operating conditions of the roadway and location of hazards on the roadside. Calculating the terms for equation 2 would require a great deal of tedious computation and data analysis.

A software solution for this problem could alleviate the computational burden while providing a framework for gathering and storing roadway and roadside characteristics. The remainder of this paper will describe a system for performing these analyses.

One problem with current cost effectiveness programs for evaluating roadside safety improvements is the difficulty of changing the encroachment, accident frequency and severity models in response to improved analyses or policy changes. Refining or revising a model in one of these programs requires a great deal of effort and expense. When a program is withdrawn from circulation and reconstructed it may lose credibility with practicing engineers. Programs for evaluating safety should encode the basic method to be used but leave as many of the details of the various models open to change since these models will almost certainly evolve in response to greater knowledge, shifting policy and economic forces. This capacity to change very deep knowledge is a primary objective of the SafetyAdvisor.

The SafetyAdvisor is a program that is being developed that will perform safety assessments of roadway segments using the basic technique outlined above. One of the unique aspects of this system is the form used to encode the assessment process. This is accomplished using an object-oriented approach to designing the software [15] [16]. Typical programs encode knowledge by specifying a sequence of operations, an algorithm. Expert systems encode knowledge as a sequence of rules-of-thumb or heuristics [17]. Object-oriented programs, in contrast, model the relationships between data elements without specifying the order in which operations must be performed. A similar object-oriented approach to roadside safety has been explored for the more restricted domain of warranting guardrails [18] [19]. This software modeled the relationships between roadway and roadside characteristics and the properties of a variety of guardrail systems stored in a database.

The roadway itself is modeled as an object with a variety of characteristics like lane width, traffic volume and speed. Hazards along the roadway are also modeled as objects having a variety of characteristics like distance from the edge of pavement and position along the roadway. These two types of objects, the roadway and hazards, correspond to their physical counterparts. Relationships between these hazard objects and roadway objects consist of methods for determining the conditional probabilities in equation 2. The software queries the dictionary of hazard and roadway elements about the probabilities of encroachment, accident, and injury accident. The roadway object can calculate the encroachment probability at a particular location because the object itself contains both the encroachment model and the characteristics of the roadway at that point. Each hazard contains models for predicting the probability of an accident occurring and an injury accident occurring. Each hazard’s model
is unique to that particular object. If changes are made in the severity model of, for example, side-slope rollovers, all the changes are contained completely within the side-slope object. Each hazard is queried about the probability of an injury accident occurring. These probabilities are passed upward to the roadway object which then sums up all the appropriate values and thereby determines the safety of the roadway.

Each of these models can be modified to suit the particular hazard. This is done by treating the model as a type of data rather than as a part of the procedure. The only restrictions on the models are that they use known characteristics of the roadway and hazards to predict the conditional probabilities and that they conform to the form of equations 3, 6 and 7.

Conclusions

Safety management will require better techniques for assessing the safety of road segments. Prioritizing various possible improvement projects or alternative design strategies requires some method for quantifying the degree of risk involved in traversing a roadway. The safety of a roadway has been defined in terms of three conditional probabilities: the probability of an encroachment, the probability an encroachment will become an accident and the probability an accident will be an injury accident. The specific details of each of these probabilistic models is dependent on the characteristics of the roadway, the roadside and the hazardous objects found there. General purpose models have been suggested that allow a wide variety of specific models to be used.

An object-oriented software tool for performing this assessment and managing the assessment process has been briefly described. The roadway is defined as an object that is in turn composed of other objects that represent the characteristics of the hazards along the roadway. The models that represent the conditional probabilities of equation 2 are objects that are uniquely attached to a specific type of hazard. Automating the process of assessing the safety of roadways would be more systematic and consistent and the software tool would establish a format for gathering and storing the data.
References


The Importance of Using a Range of Vehicle Weights When Testing a Crash Cushion

Michael G Dreznes
Vice President-International
Energy Absorption Systems, Inc
USA

and

Owen S Denman
Senior Vice President-Operations
Energy Absorption Systems, Inc
USA
The Importance of Using a Range of Vehicle Weights when Testing a Crash Cushion

Michael G Dreznes
Energy Absorption Systems Inc.
Chicago, USA

Abstract

Crash cushions should be designed to protect the majority of a country’s passenger automobile fleet at a reasonable cost. A vehicle weight range which represents 90% of the passenger cars on the road is achievable and is recommended.

Some currently proposed testing practices would allow the use of a single average weight vehicle when testing a crash cushion. If an average weight vehicle is used in testing, there is no assurance that the system will function safely for the lower or higher weight vehicles which represent a significant percentage of the vehicle fleet. Occupants of a light weight vehicle react much differently than occupants in an "average weight vehicle" due to the difference in the momentum transfer effect between the two vehicles. Occupants in a large vehicle may be subjected to intolerable accelerations because the crash cushion does not have sufficient energy absorbing capacity.

The United States currently uses a weight range of 820 kg to 2040 kg for testing crash cushions. The testing standards are being modified and will probably use a weight range of 820 to 1600 kg. The impending European harmonization provides an opportunity to develop a vehicle weight range which represents all European vehicles.

This paper will suggest that designing crash cushions to protect one weight vehicle, while disregarding the safety of the majority of the vehicle fleet, is incomprehensible. The paper will develop a proposed vehicle weight range for Europe and explain the importance of tests using a vehicle range instead of an "average weight vehicle".
THE IMPORTANCE OF USING A RANGE OF VEHICLE WEIGHTS WHEN TESTING A CRASH CUSHION
Michael G. Dreznes and Owen S. Denman
Vice President-International/Senior Vice President-Operations
Energy Absorption Systems, Inc.

1. INTRODUCTION - CHAPTER 1

A properly designed and installed crash cushion will allow occupants of a car to survive what otherwise might have been a fatal crash with a roadside hazard. Proper testing of crash cushions is necessary to ensure that these systems will function as expected when they are impacted by an errant vehicle.

This study explains the need for using both lightweight and heavyweight passenger cars when testing a crash cushion, reviews the passenger car weights used in past tests in Europe, and the appropriateness of the recently proposed CEN 226 WG1 test vehicle weight range.

2. THE NEED FOR A WEIGHT RANGE IN CRASH CUSHION TESTING - CHAPTER 2

Although crash cushions are designed to protect occupants of vehicles, it is unrealistic to conduct actual high speed crash cushion tests that include human passengers. Researchers can predict how occupants of a vehicle would react during a crash test by evaluating how the vehicle reacts during the impact. If a test vehicle responds properly during an impact, and if the vehicle deceleration levels are low, then researchers conclude that occupants in vehicles of this year, model and make should survive a design impact with the crash cushion.

Crash cushions can be designed to perform satisfactorily for almost any range of vehicles. It is possible for a crash cushion to be developed that would safely decelerate 600 kg subcompact passenger vehicles up to 40 ton heavy trucks. The cost and length of such a system would limit its usefulness and, therefore, make it an unfeasible option.

It is not cost-efficient to crash every model of every vehicle on the road today into a crash cushion. However, a crash cushion designed only for an "average weight vehicle" may be ineffective for the majority of the vehicle fleet it is being used to protect. Researchers must decide which cost-efficient vehicle weight parameters can be used to test crash cushions to ensure that the systems will function properly with the largest possible percentage of the passenger car population within the design weight range.

A crash cushion brings an errant vehicle to a controlled stop by using two very different energy-absorbing mechanisms. The first, more obvious mechanism to absorb energy is the compression of an energy-absorbing structure. A resistant force (F) is applied to the vehicle over some distance (D) which results in work (W), or the absorption of energy (E) by the crash cushion. In an idealized crash cushion, the amount of work that is done is equal to the product of
F \times D \text{ which is equal to the kinetic energy (KE) of the impacting vehicle, } \frac{1}{2} \text{ Mass} \times \text{Velocity}^2. \text{ In the form of an equation then:}

\text{Work done by Crash Cushion} = \text{Kinetic Energy of Impacting Vehicle}

\text{or}

F \times D = \frac{1}{2} \text{ Mass} \times \text{Velocity}^2

F = \text{Resisting force applied by crash cushion}
D = \text{Crush distance of the crash cushion}
M = \text{Mass of the impacting vehicle}
V = \text{Velocity of the impacting vehicle}

\text{If F is large enough to stop the heavier weight vehicles in some reasonable distance D, this same force will result in unacceptably high deceleration of the lighter weight vehicles. If F is low enough to provide acceptable deceleration rates for the lighter weight vehicles, the distance required to stop the heavier weight vehicles will be excessive. The idealized crash cushion becomes impractical when the effect of applying a single level of force (F) is considered.}(1)

The second consideration in crash cushion designs is the momentum transfer or inertial effects. This is a very important characteristic when the developer is working with a real (non-idealized) crash cushion. The characteristic can best be visualized by considering that the vehicle of some mass (M_1) at some initial velocity (V_1) impacts a crash cushion where the crash cushion with a mass (M_2) is initially at rest (initial velocity, V_2, is zero). As the vehicle impacts the crash cushion, the mass of the crash cushion is set in motion and the velocity of the impacting vehicle is reduced. Thus, momentum of the impacting vehicle is transferred to the crash cushion. In the form of an equation:

(M_1 \times V_1 + M_2 \times V_2)_{\text{initial}} = (M_1 \times V_1 + M_2 \times V_2)_{\text{final}}

The effect of the momentum transfer in the very short time period of an impact results in an impulse (I) which is the product of an applied force (F) and the time duration of the applied force (\Delta T) that is equal to the product of the mass (M) of the hardware being accelerated and the change in the velocity (\Delta V) of that mass. In the form of an equation:

\text{Impulse} = F \times \Delta T = M \times \Delta V

F = \text{Impulse force applied to the impacting vehicle}
\Delta T = \text{Time duration of the applied force}
M = \text{Mass of the hardware accelerated to some velocity as a result of the impact}
\Delta V = \text{Change in the velocity of the crash cushion hardware due to the impact}

\text{This consideration is often overlooked by developers and results in unacceptably high decelerations for the lighter weight vehicles.}
The combination of the compressive force and the impulse force must be considered for the vehicle weight and speed range for which the crash cushion is being qualified. This combined force can vary the actual deceleration by a factor of three in impacting vehicles ranging between 800 and 1500 kg. Thus, a crash cushion that is tested and acceptably evaluated at some single or average vehicle weight may not perform acceptably for the full range of vehicles for which the system is being qualified. (2)

The tests used to qualify a crash cushion need to consider the lightest and the heaviest vehicles that can be practically addressed. Testing with the lightweight vehicle will verify that tolerable deceleration levels are not exceeded, that there is no intrusion into the passenger compartment and that a stable vehicle trajectory (during and after the impact) is present. Testing with the heavier vehicle will verify that the crash cushion has sufficient energy-absorbing capacity and that the structural capacity of the crash cushion is adequate for this limiting condition.

3. HISTORY OF CRASH CUSHION TESTING - CHAPTER 3

3.1 U.S.A.

Prior to 1981, guidelines for evaluation of crash cushions in the United States designated the use of a lightweight test vehicle of 2250 pounds (1020 kg) and a heavier car of 4500 pounds (2040 kg). The range of cars which weighed between these two car weights represented about 85% of the United States car fleet. The influx of lighter, fuel-efficient cars into the United States in the 1970's was significant enough to lower the average vehicle weight as shown in Figure A. (3) This forced the authorities to revise the lightweight test vehicle weight to 1800 pounds (820 kg) in the NCHRP 230 guidelines which were published in 1981. (4) Crash cushions that were designed for the 2250 lb vehicles and were in use on the U.S. roads were expected to be modified to safely decelerate these lighter weight cars. Some systems could not meet the new requirements and therefore became obsolete, or their use was greatly limited.

FIGURE A - AVERAGE CURB WEIGHT OF U.S. CARS
One product affected by the NCHRP 230 vehicle weight modification was the water-filled "Hi-Dro" crash cushion, manufactured by Energy Absorption Systems, Inc. An impact of a small car weighing between 820 and 1020 kg with the "Hi-Dro" crash cushion would subject the occupants to higher deceleration levels than with the 1020 kg car. This is an excellent example of a crash cushion that would work with a hypothetical average car, weighing 1020 kg or more, but did not give the desired protection to occupants of a lighter car. The existence of the requirement to test a crash cushion using cars that represented the country's vehicle weight range, instead of just an average weight, encouraged the development of new technology and safer roads for motorists on the United States highways.

3.2 Europe

European crash cushion testing parameters to date have concentrated primarily on singular test vehicle weights, as shown in Table A. Crash cushions in some countries in Europe are being tested with a 1250 kg car, which is considered the average weight vehicle for those countries. Other European countries are using either 1000 kg or 1500 kg test vehicles. Often, when evaluating crash cushions, researchers will use one of the heaviest cars on the road to test for structural adequacy (as is the case with the TRRL test in the UK). This is logical and appropriate. However, these crash cushions will also be hit by lighter cars. Tests must be run with these cars as well as with the large cars to predict how the occupants will react during the impact.

<table>
<thead>
<tr>
<th>Country</th>
<th>Test Institute</th>
<th>Year</th>
<th>Test Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>ONSER (INRETS)</td>
<td>1971</td>
<td>970 kg &amp; 1270 kg</td>
</tr>
<tr>
<td>France</td>
<td>INRETS</td>
<td>1977/1988</td>
<td>1250 kg</td>
</tr>
<tr>
<td>Netherlands</td>
<td>SWOV</td>
<td>1982</td>
<td>753 kg</td>
</tr>
<tr>
<td>Sweden</td>
<td>VTI</td>
<td>1985</td>
<td>1070 kg</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>TRRL/MIRA</td>
<td>1988</td>
<td>1500 kg &amp; 1380 kg</td>
</tr>
<tr>
<td>Italy</td>
<td>AUTOSTRADIE</td>
<td>1988</td>
<td>1070 kg &amp; 1360 kg</td>
</tr>
<tr>
<td>Germany</td>
<td>BAST</td>
<td>1990</td>
<td>900 kg &amp; 1360 kg</td>
</tr>
</tbody>
</table>

According to reports published by SETRA in 1988 (5) and the German/French Experts for Passive Safety in 1977 (6), 1250 kg vehicles were used by INRETS during crash cushion testing. While this 1250 kg vehicle could be a good vehicle for testing system capacity and structural adequacy of a crash cushion in Europe, it should not be used to evaluate crash cushions for occupant risk in the lighter weight vehicles. Tests on crash cushions run in France in 1971 used vehicles ranging between 970 and 1270 kg.(7) Why this practice of using a vehicle range was stopped in favor of the 1250 kg average weight vehicle is unclear.

Italian researchers, realizing the vast differences in car weights in Italy, have used ranges of vehicles when testing crash cushions.(8) In 1988, tests were run using a fully loaded Opel Kadett, weighing 1070 kg and a Fiat 131, weighing 1380 kg.

In 1982, to determine a proper average vehicle weight for testing, the SWOV in the Netherlands eliminated the top 7-1/2% of the heaviest cars and 7-1/2%
of the lightest cars on their roads. (9) This 85% of the passenger car population was considered an acceptable proportion of the population for testing.

A range of vehicle weights, and not just an average weight vehicle, is necessary to properly evaluate a crash cushion. A realistic car range that will encompass the great majority of the cars being used in Europe must be developed.

4. THE CAR POPULATION IN EUROPE - CHAPTER 4

Passenger cars represent 87% of the vehicles on the roads in Europe. The number of passenger cars in Europe has increased by 80% since 1972. This number is projected to increase by an additional 40% over the next 20 years. (10) Steps must be taken to ensure that the crash cushions used on European roads will adequately protect the occupants in as many of these cars as possible.

A large difference currently exists between car fleet weights in different countries in Europe. For example, the weighted mean curb weight of cars in Italy is about 32% less than the mean curb weight of cars in Sweden. How safe could a Swedish driver feel in Italy, if he knew that their road furniture was only designed for cars that weighed 32% less than his car? To develop a separate vehicle weight range for each European country would satisfy the need for that country, but would negate the entire reason for harmonization.

In some European countries, the range of vehicle weights today is fairly narrow. This could conceivably allow for a smaller effective vehicle weight range than the other countries. However, with the anticipated easing of European tax and duty regulations in 1992, cars manufactured in other European countries will be integrated into every country's vehicle fleet. The less restrictive employment regulations anticipated for 1992 will also result in more movement of people among the countries in Europe. These people will use their own cars. The vehicle weight range in each country may expand, resulting in a more uniform vehicle range among countries. The crash cushions that worked with today's average weight vehicle in a country may or may not perform satisfactorily for a substantial portion of a country's actual vehicle population tomorrow.

5. PROPOSED CEN 226 WG1 CRASH CUSHION VEHICLE WEIGHT RANGE - CHAPTER 5

The European community is taking extensive actions to harmonize its road network regulations by the end of 1992. Recognizing the need for testing both light and heavy cars, the CEN 226 WG1 has informally proposed that a vehicle weight range of 800 kg to 1250 kg be considered for crash cushion evaluation.

This study analyzes the feasibility of this test vehicle range for the European car population.

5.1 Method of Evaluation

The 30 car models with the largest sales volumes in 1988 and 1989 in Belgium, France, Italy, Netherlands, Portugal, Spain, Sweden, the United Kingdom and West Germany were used as a sample population for this study.
These nine countries were selected because they give an adequate representation of the Western European car population, and these countries have tested and/or installed crash cushions. The total car population in these nine countries represented about 89% of the cars on the West European roads as of December 31, 1989.

Sales of the 30 car models with the greatest sales volumes in the nine subject countries in both 1988 and 1989 totaled 19,600,000. These cars were sorted by weight to determine their weighted distribution in each country.

**TABLE B - EUROPEAN PASSENGER CAR SALES**

<table>
<thead>
<tr>
<th>Country</th>
<th>Population of All Cars (000)</th>
<th>1989</th>
<th># of Cars (000)</th>
<th>Range (kg)</th>
<th>Weighted Mean (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>3,600</td>
<td>604</td>
<td>640-1330</td>
<td>947</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>23,000</td>
<td>3,816</td>
<td>640-1950</td>
<td>920</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>25,000</td>
<td>3,928</td>
<td>620-1330</td>
<td>873</td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>5,400</td>
<td>663</td>
<td>610-1245</td>
<td>934</td>
<td></td>
</tr>
<tr>
<td>Portugal</td>
<td>1,600</td>
<td>353</td>
<td>640-1150</td>
<td>857</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>11,500</td>
<td>1,896</td>
<td>640-1210</td>
<td>894</td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>3,600</td>
<td>520</td>
<td>720-1390</td>
<td>1,149</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>19,400</td>
<td>3,594</td>
<td>645-1410</td>
<td>1,011</td>
<td></td>
</tr>
<tr>
<td>West Germany</td>
<td>30,200</td>
<td>4,213</td>
<td>700-1425</td>
<td>1,021</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>123,300</td>
<td>19,587</td>
<td>610-1950</td>
<td>954</td>
<td></td>
</tr>
</tbody>
</table>

The percentage of the 30 car models with the greatest sales volumes in each country that fit into a range which is 5% over to 5% under the country's average weighted curb weight, was then calculated to determine the feasibility of using an average weight vehicle for crash cushion testing. The country distributions were further used to calculate the percentage of sample population within the proposed CEN weight range. Finally, an analysis was made to determine the number of cars in each country which fit into the range that included 5% over and 5% under the weight of the test vehicles previously used in those countries to test crash cushions.

**5.2 Results**

Proponents of a single weight test vehicle may use the argument that occupants of vehicles weighing close to the test vehicle weight will respond similarly to the occupants of the test vehicle. This may or may not be true. Tests have shown that crash cushions which meet certain occupant risk parameters for one weight car will not meet those parameters when impacted by a car weighing as little as 5% more or less than the original test vehicle. However, for the purpose of this study, it is assumed that occupants of one weight car will react basically the same in cars weighing 5% more or 5% less than this test car.

These parameters were used to evaluate the appropriateness of using a country's average weighted mean vehicle as a test vehicle, as well as for evaluating the effectiveness of the cars previously used by European testing agencies for crash cushion tests. The analysis of this data is summarized in TABLE C.(11)
Using an average weight vehicle to test a crash cushion will not ensure adequate protection for the car fleet of the country. As demonstrated in Table C, only a small percentage of the car population is included in a range that is 5% over and 5% under the weight of the country’s average car.

Crash cushion manufacturers would prefer to design systems that are only tested to this average weight. It would keep the cost of their systems down, but the systems may or may not work with the majority of the cars on the road.

Testing a crash cushion with only the 1000 kg, 1250 kg, or 1500 kg car will provide even less assurance of proper protection. These single median weights make it easier to design a crash cushion, however, they do not represent an adequate percentage of the vehicles the crash cushion is being designed to protect.

Sweden is the anomaly of the countries studied. Because of the presence of many large vehicles, the CEN proposed range would only cover about 59% of the Swedish cars in the study. The other European countries may also consider testing both an 800 kg and a 1400 kg vehicle. This would ensure protection for a range of vehicles that represents 87% of the cars in this study. This heavier car test would reduce the possibility of a crash cushion failing to perform due to a lack of capacity. The additional capacity may provide additional protection to lightweight cars traveling at over design speeds.

The percentages of the study population represented by ±5% of the average weight vehicle, the 5% over and 5% under the test vehicle weights of previous European tests, the proposed CEN weight range (800-1250 kg), and the 800-1400 kg weight range are shown in Table C.

### TABLE C - RELATIONSHIP OF EUROPEAN CAR POPULATION TO TEST VEHICLE WEIGHTS

<table>
<thead>
<tr>
<th>Country</th>
<th>Average Vehicle Weight (±5%)</th>
<th>Previous Test Vehicle Weight (±5%)</th>
<th>800-1250 kg CEN Weight Range</th>
<th>800-1400 kg Proposed Weight Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>29%</td>
<td>--</td>
<td>89%</td>
<td>91%</td>
</tr>
<tr>
<td>France</td>
<td>17%</td>
<td>2% (INRETS)</td>
<td>86%</td>
<td>87%</td>
</tr>
<tr>
<td>Italy</td>
<td>19%</td>
<td>14% (AUTOOSTRADE)</td>
<td>75%</td>
<td>76%</td>
</tr>
<tr>
<td>Netherlands</td>
<td>23%</td>
<td>9% (SWOV)</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Portugal</td>
<td>35%</td>
<td>--</td>
<td>76%</td>
<td>76%</td>
</tr>
<tr>
<td>Spain</td>
<td>32%</td>
<td>--</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Sweden</td>
<td>14%</td>
<td>11% (VTI)</td>
<td>59%</td>
<td>97%</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>30%</td>
<td>0% (TRRL)</td>
<td>92%</td>
<td>96%</td>
</tr>
<tr>
<td>West Germany</td>
<td>13%</td>
<td>67% (BAST)</td>
<td>84%</td>
<td>92%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>23%</td>
<td>--</td>
<td>83%</td>
<td>87%</td>
</tr>
</tbody>
</table>
6. SUMMARY - CHAPTER 6

Properly designed and tested crash cushions will make the European roads safer. Occupants of different weight passenger cars will not react the same during an impact with a crash cushion. Researchers must consider the passenger car population of the entire European community, as well as the "state of the possible" when developing the guidelines for these crash cushions.

While the proposed CEN 226 WG1 test weight of 800 kg to 1250 kg is better than an average weight vehicle, it is possible to design crash cushions that will function with 800 kg to 1400 kg passenger cars. Testing with an 800 kg and a 1400 kg vehicle will provide protection for 87% of cars in the sample population for this study.

The CEN 226 WG1 should consider changing the heavyweight passenger car weight to 1400 kg. Using the 1400 kg test vehicle instead of the 1250 kg test vehicle will assure protection for an additional 4% of the passenger cars on the European roads. Based on 1989 figures, this represents about 6,000,000 passenger cars. If the expanded test range is used and higher capacity crash cushions are installed, the European roads will be safer for these 6,000,000 motorists. Certainly their lives are just as valuable as the passengers in the smaller vehicles.

*****
7. REFERENCES - CHAPTER 7


7. "Summary of research completed since 1971", O.N.S.E.R.

8. "A Maintenance-Free Median Barrier End Treatment" report presented to the TRB A2A04(2) Subcommittee by Francesco La Camera in January 1989 containing test results from crash tests of November 19 and 30, 1988; Test No. 31: 0 degree impact of Opel Kadett at 100 km/m, Test No. 33: 10 degree Lancia Fulvia at 85 km/m, Italy.


15. INRETS Test Results for SODIREL Crash Cushion, Normal VL TEST IN-ATS-03/628, June 9, 1987.


Reliability of Crash Tests Into Segmented Concrete Barriers

Francis P D Navin
Dr, P Eng

Robert Thompson
M A Sc

Michael MacNabb
B A Sc

and

Douglas Romilly
Dr
Accident Research Team
Faculty of Applied Science
University of British Columbia
U S A
The services of crash tests were conducted at 60, 80 and 1800 km/hr, at impact angles of 15, 20 and 25 degrees, with small and medium size sedans into two different heights of segmented concrete roadside barriers. The purpose of the tests was to observe the performance of the barriers and vehicles relative to the performance limits specified by NCHRP 230.

The vehicles were all instrumented with accelerometers and the result samples at 3000 Hz on each of nine channels for a total of 12 seconds. This data was fastened by a low-pass sixth-order Butterworth filter with a cut-off at 180 Hz as specified by NCHRP 230. In addition, high speed videos at 1000 frames per second were overhead and behind the barrier to obtain a visual record of the vehicles and barrier behaviour.

The result is a thorough description of vehicle and barrier performance at speeds loading up to the NCHRP 230 test speeds. Also, a reliability based approach from some early analytical studies given the probability that the results are meaningful given information the statistical matter of the data observed. The reliability method will outline how much variability is allowed in the testing procedures and what variables must be strictly controlled.
1. INTRODUCTION

The British Columbia Ministry of Transportation and Highways (MoTH) has since the 1950's developed a family of segmental concrete barriers. The early roadside concrete barrier was an 18 inch high, segmented device which was essentially elliptical in shape. The design was a simple variation of the DAV barrier which was used in Europe at about the same time. The literature of the day indicated that, for medium size vehicles of 1200 kg, it worked reasonably well at impact angles of 15 to 20 and speeds below 80 km/h.

The next family of concrete barriers originated in 1968 and used the North American experience with the New Jersey cross section, but were somewhat lighter. The segmental design was continued because the mountainous topography requires considerable maintenance behind roadside barriers. Also, the vistas from the road are a major tourist attraction, therefore the roadside barriers had to be as low as possible so a reasonably large number of vehicle occupants would have ample lateral visibility. The importance of the median barrier to road safety required that it be larger than the roadside barrier. Both barriers have a mass and dimensions that make them easy to handle by truck mounted lifting equipment and aesthetic when placed in large quantities. Early computer studies with HVSOM indicated that the segmented barriers would satisfactorily redirect vehicles and generally meet the 15 g limit of lateral acceleration.

The British Columbia Ministry of Transportation and Highways decided to experimentally test the segmented barriers after two decades of successful in-service operation. The main purpose of the testing was to observe, under experimental conditions how the barriers performed with vehicles that were typical of the provincial passenger car fleet.

This report describes the experimental tests of the barriers, the results and a proposed reliability based procedure to evaluate the experimental outcomes and suggests further research.

2. SEGMENTED BARRIERS

The province of British Columbia has a population of about 3 million, covers 949,000 square km, has five major mountain ranges running from North West to South East, and is subject to great amounts of rain and or snow. The sparseness of the population and length of the roads in very rugged terrain, with a harsh environment requires continual maintenance of the highway alignment. Also the style of road building and upgrading in the province is quite incremental, the least difficult sections being completed early and the very difficult and expensive
construction being done as finances permit. These conditions and approaches to road building require flexibility so the pavements are made of asphalt and the barriers are segmented concrete. The best mountain highways are usually constructed as expressways with paved shoulders. The median has a barrier, often continuous and the shoulders have about 0.6 m paved distance behind the barrier.

The segmented concrete roadside barrier is shown in Figure 1. The sections are 2.5 m long, 690 mm high, 550 mm at the base, 208 mm at the top and shaped generally to follow the New Jersey barrier. The barrier's mass is about 1100 kg. Each section has two transverse holes to take a pipe used in lifting, two bottom drains are included occasionally and the bottom is hollow to allow for better stability. The details of the connections between male and female ends are also shown. The arrangement of male and female units simplifies road maintenance behind the barrier. To make an opening in the barrier, a few female units are removed and then the male units. Installation is equally as simple and relatively fast with truck mounted lifting equipment.

The median barrier is 810 mm high, 2.5 m long, 600 mm at the base, 232 mm at the top with the same general shape as the roadside barrier. The median barrier's mass is about 1650 kg. These were the barriers that were tested.

**Figure 1.**

*690mm CONCRETE ROADSIDE BARRIER*

---

VTI RAPPORT 372A
3. THE CRASH TEST

The roadside barrier crash testing was performed by the Accident Research Team from Civil Engineering at UBC. The site was an abandoned airfield taxi way used for vehicle testing. The test matrix was developed using the ideas from NCHRP 230, in particular the angle of impact. The vehicles selected, 900 kg and 1200 kg, reflect the British Columbia passenger car fleet. The speeds used were: 60, 75, 96 km/h and later about 80 km/h. These speeds were chosen to study barrier performance rather than simply adherence to the NCHRP 230 performance criteria.

None of the barriers were tested at the recommended NCHRP 230 limit of a 2040 kg vehicle at 96 km/h at 25 degrees. The reason for this was in part the lack of suitable 2040 kg passenger cars in the fleet of vehicles available from the salvage yard at the Insurance Corporation of British Columbia. Also at the outset of testing such a vehicle was considered to be obsolete within the passenger car fleet and that it was unlikely to come back into common use. The more easily available and representative 900 kg and 1200 kg vehicles were employed. The angles were used to maintain compatibility with other tests. The speeds were increased to observe the behaviour of the barriers and to gain experience with the experimental equipment.

The crash test results are summarized in Table 1. The first observation is that the lateral deceleration estimated from the formula proposed by Olsen (1974), Equation 1, gives a reasonably good estimate of the values observed from the accelerometers, see Figure 2. The solid lines of Figure 3 are the estimate of lateral acceleration from the data and the dashed line from the estimate by Olsen’s formulation. The values are in very good agreement. This is a fortunate result since it allows Olsen’s formula to be used in preliminary analysis of barrier forces. A similar curve for the maximum barrier displacement is given in Figure 4. The curves are of course specific for the barriers used in British Columbia.

Figure 2.

OBSERVED AND ESTIMATED LATERAL ACCELERATIONS

VTI RAPPORT 372A
### Table 1
Impact Test Results
Segmented Concrete Barriers

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Type</th>
<th>Mass (kg)</th>
<th>V (km/h)</th>
<th>Θ (°)</th>
<th>a_y (g)</th>
<th>D (m)</th>
<th>A_y (g)</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>890</td>
<td>60</td>
<td>15.1</td>
<td>-</td>
<td>0.08</td>
<td>1.9</td>
<td>1700</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>890</td>
<td>63</td>
<td>24.5</td>
<td>3</td>
<td>0.17</td>
<td>3.5</td>
<td>3080</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>1190</td>
<td>60</td>
<td>25.1</td>
<td>3</td>
<td>0.26</td>
<td>2.7</td>
<td>3160</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>1190</td>
<td>75</td>
<td>24.8</td>
<td>4</td>
<td>0.33</td>
<td>3.3</td>
<td>3870</td>
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<td>5</td>
<td>M</td>
<td>910</td>
<td>76</td>
<td>15</td>
<td>2.5</td>
<td>0.19</td>
<td>2.3</td>
<td>2070</td>
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<tr>
<td>6</td>
<td>M</td>
<td>880</td>
<td>78</td>
<td>21.6</td>
<td>3.5</td>
<td>0.31</td>
<td>3.3</td>
<td>2800</td>
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<tr>
<td>7</td>
<td>RS</td>
<td>910</td>
<td>78</td>
<td>15</td>
<td>3</td>
<td>0.21</td>
<td>2.6</td>
<td>2410</td>
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<tr>
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<td>78</td>
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<td>RS</td>
<td>1200</td>
<td>75</td>
<td>24.2</td>
<td>2</td>
<td>*</td>
<td>3.6</td>
<td>4320*</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>890</td>
<td>94</td>
<td>13.9</td>
<td>2.5</td>
<td>0.35</td>
<td>2.9</td>
<td>2610</td>
</tr>
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<td>11</td>
<td>M</td>
<td>1200</td>
<td>93</td>
<td>15</td>
<td>-</td>
<td>0.36</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
<td>900</td>
<td>90</td>
<td>25</td>
<td>-</td>
<td>0.84</td>
<td>-</td>
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<tr>
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<td>M</td>
<td>1200</td>
<td>93</td>
<td>25</td>
<td>-</td>
<td>1.44</td>
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<tr>
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<td>RS</td>
<td>895</td>
<td>65</td>
<td>25</td>
<td>-</td>
<td>1.59*</td>
<td>-</td>
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<td>15</td>
<td>RS</td>
<td>1200</td>
<td>60</td>
<td>25</td>
<td>-</td>
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<td>-</td>
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<td>RS</td>
<td>1200</td>
<td>83</td>
<td>20</td>
<td>-</td>
<td>1.19*</td>
<td>-</td>
<td>-</td>
</tr>
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<td>16a</td>
<td>RS</td>
<td>1185</td>
<td>82</td>
<td>20</td>
<td>-</td>
<td>0.74</td>
<td>-</td>
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<tr>
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<td>RS</td>
<td>1200</td>
<td>81</td>
<td>20</td>
<td>-</td>
<td>1.73*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>RS</td>
<td>915</td>
<td>83</td>
<td>25</td>
<td>-</td>
<td>1.74*</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

RS = Roadside Barrier  
M = Median Barrier  
a_y = Estimated Olsen's formula

**Figure 3.**
AVERAGE LATERAL ACCELERATION BY IMPACT SPEED AND IMPACT ANGLE SEGMENTED CONCRETE BARRIER

**Figure 4.**
MAXIMUM BARRIER DISPLACEMENT BY IMPACT SPEED AND IMPACT ANGLES SEGMENTED CONCRETE BARRIERS
Table 1 - continued

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Type</th>
<th>Climb cm</th>
<th>Redirection</th>
<th>Separation</th>
<th>Peak Acceleration</th>
<th>High Speed</th>
</tr>
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<td>1</td>
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<td>0.30</td>
<td>Smooth</td>
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</tr>
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<td>M</td>
<td>0.43</td>
<td>Smooth</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>0.37</td>
<td>Smooth</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>0.47</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>0.27</td>
<td>Smooth</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>0.37</td>
<td>Smooth</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>RS</td>
<td>0.28</td>
<td>Smooth</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>RS</td>
<td>0.50</td>
<td>Smooth</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>RS</td>
<td>0.69</td>
<td>Smooth</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>-</td>
<td>Smooth</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>11</td>
<td>M</td>
<td>40</td>
<td>Smooth</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
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<tr>
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<td>RS</td>
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<tr>
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<td>RS</td>
<td>44</td>
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<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>16</td>
<td>RS</td>
<td>39</td>
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<td>No</td>
<td>No</td>
</tr>
<tr>
<td>16a</td>
<td>RS</td>
<td>27</td>
<td>Smooth</td>
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<td>No</td>
<td>No</td>
</tr>
<tr>
<td>17</td>
<td>RS</td>
<td>49</td>
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<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>RS</td>
<td>53</td>
<td>Smooth</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

M = Median Barrier
RS = Roadside Barrier

The behaviour of the roadside barrier was also investigated to estimate at what speed it would separate or pull apart. In all cases the impacting vehicles were successfully redirected (test 9 depends on where the deflection angle is measured) but the barrier did break. The energy level for this appears to be almost 82 km/h at 20 degrees for a vehicle of 1200 kg. The median barrier only separated on one occasion and, based on the tight grouping of the two breaks of the roadside barrier the separation probably occurs at about 93 km/h, 25 degrees for a vehicle of 1200 kg.
4. PERFORMANCE ESTIMATE

Olsen (1974) has derived a formula to estimate the average lateral acceleration into a roadside barrier as:

\[ a_y = \frac{V_0^2 \sin^2 \theta}{2g \left[ A \sin \theta - \frac{B}{2} (1 - \cos \theta) + D \right]} \]

where

- \( V_0 \) = vehicle's forward speed at impact
- \( \theta \) = impact angle
- \( A \) = distance, front to CG of vehicle
- \( B \) = width of vehicle
- \( D \) = displacement of barrier

It is well known that the angle of impact is dependent on vehicle speed. Nevin (1991) has shown that an approximate relationship of the angle of impact given; speed, tire condition, road width and road condition is:

\[ \theta = 90 - \sin \left[ 1 - \frac{W}{V^2} g (0.90 - 0.0049V) \right] \]

where

- \( W \) = roadway and shoulder width
- Rand = uniform random variable, 0 to 1
- \( g = 9.81 \text{ m/s}^2 \)

This particular formula is quite simple to use since it depends only upon easily observed and measured variables. To get the equations into a more useful form, the force imposed by the impacting vehicle and the resisting force of the barrier is used as a strength measure and is given by:

\[ F_v = m_v a_y \]

The expected distribution of this force using the vehicle fleets of 1975 and 1990 was estimated by Monte Carlo simulation. The 1975 fleet was selected as being reasonably representative of the vehicle fleet at the time NCHRP 230 was developed. The current 1990 fleet is used simply for comparison purposes.

The simulation results are given in Figure 5. The difference between the 1990 impact curve and that for 1975 is attributable to the reduced vehicle mass. The average speed was held constant at 100 km/h. The assumed NCHRP 230 "operational limit" of the force on the barrier be set at a 2040 kg vehicle with an average declaration of 9 g. The probability of a vehicle in 1975 exceeding that value is about 1 in a 100. The chances of a passenger car in the 1990 fleet doing the same is about 3 in a 1000, see Table 2.
Figure 5.
FREQUENCY OF BARRIER IMPACT FORCE
BY YEAR AND BARRIER DEFLECTION
(V = 100Km/h, 2 lanes each direction)

Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Data</th>
<th>Chance of non-compliance</th>
<th>Most likely combination for ay = 9g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>v</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>kg</td>
<td>km/h</td>
<td>kg</td>
</tr>
<tr>
<td>1975</td>
<td>1360</td>
<td>100</td>
<td>1.2:100</td>
</tr>
<tr>
<td>D = 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>900</td>
<td>100</td>
<td>3:1000</td>
</tr>
<tr>
<td>D = 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>900</td>
<td>100</td>
<td>7.7:10^-6</td>
</tr>
<tr>
<td>D = 0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* \(\theta^*\) estimated from Equation 2
The expected or average estimate of the force on the barrier is: when \( D = 0 \), in 1975 about 8200 kN, in 1990 about 5200 kN; when \( D = 0.3 \) m, in 1990 it is about 3500 kN. The reduction in the expected value of the force is not as dramatic as the reduction in the highest force estimates.

The performance of the British Columbia roadside and median barrier obviously benefits from the ability to deflect. An average deflection of 0.3 m was used but the roadside barrier actually experienced deflections up to 0.74 m and the median barrier up to 1.44 m without separation.

The methods of reliability analysis (see Foschi 1988, Folz 1989) may be used to estimate the probability that the forces demanded by the impacting automobile exceed some set value. In this case the set values are set at an assumed "operational limit" and an assumed "ultimate limit". These limits have been set by the authors as being 2040 kg x 9g and 2040 kg x 15g respectively. The results of Table 2 come from solving the design equation [4]

\[
G(X) - m_v a_y - F_v \leq 0
\]

The probability that an impacting vehicle in the 1975 North American passenger car fleet produced a force greater than 2040 kg x 15g is about 2.4 in 10000 if all the variables are random and there is only random chance. The estimate for exceeding the assumed operational limit is about 1.2 in 100. This compares favourably with the value of 1 in 100 found by Monte Carlo simulation.

The reduction in the expected passenger car impact force as a result of the reduced size of vehicles is shown by the curve for the 1990 fleet with deflection (D) set to zero. The probability of exceeding the assumed ultimate limit by random chance alone is about 6.6 in \( 10^{-6} \). The random chance of exceeding the assumed operational limit is 3 in 1000 or roughly one order of magnitude less than that in 1975.

The segmented barrier as used in British Columbia is allowed to deflect. For this analysis an average deflection of 0.3 m was used. The chance of exceeding the ultimate limit was 6 in \( 10^{-12} \) and the operational limit was 7.7 in \( 10^{-6} \). Probably more meaningful for the segmented barrier is the force estimated to cause separation with the existing joint connections. For the roadside barrier this was about 4.5 kN and 6.8 for the median barrier. The Monte Carlo results gave a chance of exceeding these values roughly 25 in 100 and 4 in 100 respectively. Note that the median barrier was assumed to be located at the roadside barrier location.

The sensitivity of the variables was found to be; mass, road-tire condition, and speed. The road-tire condition determines the expected angle of impact for an out of control vehicle.

This analysis is used to demonstrate how barrier strength characteristics might be selected at an early stage of engineering. The actual values are reasonably representative but are preliminary and the underlying data must be refined further.
5. FURTHER RESEARCH

The first element of research is to develop a good model for the mechanics of separation and penetration of the segmented barrier. The model should incorporate: vehicle mass, speed, barrier mass and various mechanical interactions as well as road conditions and tire properties. This would give engineers a good understanding of the interaction of random events that can be studied by both Monte Carlo simulation and reliability methods.

The influence of human error should be investigated since random errors usually account for only 20 percent of engineering outcomes that do not meet expectations. The consequence of non-compliance must also be understood. This requires a good risk analysis so that truly important outcomes are studied.

There should be some understanding of allowable risks. The risk study must consider the benefits and costs of the various barrier schemes at typical sites so that appropriate guidance may be given the engineer during the analysis and design phases.

6. CONCLUSIONS

The British Columbia Ministry of Transportation and Highways has developed a unique set of segmented roadside and median concrete barriers. They have performed satisfactorily over the last two decades. The barriers were subjected to 19 performance tests using vehicles of 900 and 1200 kg, impact angles of 15, 20 and 25 degrees, and speeds of 60, 75, 80 and 96 km/h.

The test procedures followed the ideas of NCHRP 230. The purpose of the tests was to study the experimental performance of the barriers under conditions consistent with those found in British Columbia. The large 2040 kg passenger car of NCHRP was rejected as obsolete and the intermediate 1200 kg car was used.

The barriers redirected the vehicles within the criteria set out in NCHRP 230 with one possible exception. Test 9, the redirection depends on exactly when the angle is measured. The barriers broke on a number of occasions but the vehicles never penetrated the barrier. The barrier performance was considered good for the tests that were conducted.

The vehicles’ observed average lateral acceleration was found to be estimated well by Olsen’s formulation. The equation was extended by including a relation between angle of impact, impact speed, roadway width, coefficient of friction and environmental conditions. This equation implied that for British Columbia, the probability of the 1975 passenger car fleet exceeding the NCHRP 230 "operational limit" was about 1:100. The probability that the 1990 passenger car fleet exceeds that value is about 3:1000. The probability that the 1990 passenger car fleet impact will exceed the separation force is about 25:100 for the roadside barrier and 4:100 for the median barrier.

The procedures suggested in this paper should give the engineer a consistent method to estimate the appropriate barrier strength, given the location and type of highway involved.
7. ACKNOWLEDGEMENTS

The B.C. MoTH has funded the majority of this work but assistance has come from U.B.C. Civil Engineering and the Accident Research Team. Assistance has also been provided by Transport Canada through the Accident Research Team, the pacific Traffic Education Centre and the Insurance Corporation of British Columbia. Ms. Ronda Zheng helped with the calculations.

8. REFERENCES


NAVIN, F. 1990. Safety Factors for Road Design: Can They be Estimated? TRR 1280, Transportation Research Board.


Safe Road Design as Limit State

Francis P D Navin
Dr, P Eng
Accident Research Team
Department of Civil Engineering
University of British Columbia
USA
1. INTRODUCTION

Engineering analysis forecasts future outcomes which are usually plagued by uncertainty. Some engineering disciplines such as structures are based on a well defined design process, precise mathematical models with small to moderate variance in the design variables. Transport and highway engineering have less well defined design processes and the estimates of future performance have a very large variance. These differences are more apparent than real when it comes to actual techniques to solve many problems, the underlying processes are surprisingly similar.

This paper outlines the necessary conditions to use limit states design or reliability based techniques to understand the random elements of many highway safety problems. The method is a direct application of the reliability based procedures most fully developed in structural engineering, see Folz and Foschi (1989).

2. RELIABILITY METHODS

Virtually all civil engineering calculations are used to forecast the future performance of some uncertain system. To actually forecast the performance the engineer must first have some reasonable understanding of the system's behaviour, an adequately precise model of its behaviour and some idea of an adequate level of safety. Each of these steps introduces uncertainty and errors into the process. This paper concentrates only on dealing with random errors in the model’s variables and estimating the chance that the system will meet some engineer-defined level of performance. There is considerable literature in civil engineering dealing with maximum expected values such as Benjamin and Cornell (1970), and Ang and Tang (1984). It can be argued that reliability techniques are simply an extension of more traditional methods, see Navin (1991).

The basic idea underlying reliability analysis is to consider that there is some random demand by drivers for a particular measurable characteristic such as stopping sight distance. Also there is some supply of sight distance at a particular point along the road. The possible random relationship for these two variables is shown in Figure 1.

The difference between the expected supply and expected demand is defined as the margin of safety, which is:

\[ M - E<S> - E<D> \]
The shaded area of Figure 1 is the area where demand exceeds supply and is by definition non-compliance or failure. The word failure must be used with discretion since it is simply the demand for an engineering characteristic exceeding that available. The consequence of this outcome must be considered separately.

The inverse of the coefficient of variation of the margin of safety distribution is defined as the Safety Index or Reliability Index, given in equation 2.

\[ \beta = \frac{M}{\sqrt{\text{Var}(S) + \text{Var}(D)}} \]

The measures given by M and \( \beta \) are useful and can be made more useful by considering the design equation for checking ultimate limit states. The design equation for structural engineering provides an easily understood example and is:

\[ \phi R = \alpha D + \gamma \psi (\alpha L + \alpha Q + \alpha T) \]

where
\[
\begin{align*}
\phi & = \text{resistance or performance factor} \\
\gamma & = \text{importance factor} \\
\psi & = \text{load combination factor} \\
\alpha & = \text{load factor} \\
R & = \text{nominal resistance of a structural element} \\
D,L,Q,T & = \text{specified loads; D for dead load, L for live load, Q for wind and earthquake, T for all others.}
\end{align*}
\]

The "ultimate limit state" is a failure that is considered life threatening, usually some catastrophic structural collapse. There is also a "serviceability limit state" when failure is defined to occur when the structure no longer provides the expected performance. Failure is defined by the engineer. The design equation helps the engineer arrive at an acceptable expected frequency of non-compliance if all non-compliance is due to random events. The performance factor reflects the anticipated variations in nominal strength due to variations in materials, dimensions and workmanship. The importance factor relates the consequences of non-compliance to use and occupancy of the building. The load combination factor reduces the probability if a number of loads from different sources are acting together. The load factor takes into account the possibility of loads larger than those anticipated to act on the structure, the uncertainty involved in predicting the loads, and the approximations in the analysis of the loads on the structure.

The actual solution of the design equation requires the definition of a performance function G as given in equation 4.

\[ G(X) = \phi S_o - \alpha D_o \leq 0 \]

The subscript \( o \) represents some nominal or characteristic value of the demand and supply. The failure mode is found when \( G \) is zero or some negative value. This equation actually defines the relative behaviour of the design equation and its performance factor. A simple analogy is to think of \( G \) as single point on the horizontal axis of Figure 1 at \( \phi S_o = \alpha D_o \). The area under the curve represents the chance of non-compliance. If \( \phi \) is made smaller the whole supply curve is
4. EXAMPLE APPLICATIONS

4.1 Stopping Sight Distance

Highway engineers do not know the level of safety of their design beyond the fact that, since the design meets certain standards, it is considered safe enough. It was this question that led Navin (1990) to apply the technique to estimate the probability of non-compliance at isolated highway geometric elements. A more interesting extension by Navin and Zhang (1991) is the calibration of the Transportation Association of Canada (formerly Roads and Transportation Association of Canada (RTAC) stopping sight distance design values. The performance function was:

\[ G(z) = SSD_H - \left( V_D T_D + \frac{V_D^2}{2a_{x,H/M}g} \right) \]

where

- SSD$_H$ = highway supplied distance, TAC Standard
- V$_D$ = speed selected by the driver
- T$_D$ = perception-reaction time of drive
- a$_{x,H/M}$ = deceleration of vehicle on some highway surface
- g = gravity constant.

All the demand variables were treated as normal and independent and the second order reliability method (SORM) was used. A simple Monte Carlo simulation of the demand portion of equation 5 shows that a log normal distribution best represents the demanded SSD.

The results gave some interesting insights to the potential failure modes as $\beta$ (reliability index) and $\phi$ (performance factor) were varied by vehicle type and road-surface-tire-condition, see Figure 2. First, only a car on a dry road followed the expected decay curve of $\beta$ versus $\phi$. Vehicles on a wet road at low values of $\phi$ have almost constant $\beta$ values that then decrease with $\phi$. The sensitivity analysis indicates that on wet pavements, a$_{x,H/M}$ is the most important variable while on dry pavements speed and perception-reaction-time are most important. The probability of non performance under emergency braking was found to be about 1 in 4000 for a truck on wet pavement, about 1 in 3,500,000 for a car under similar conditions and for a car on a dry pavement it would rarely fail to perform.

This paper was also unique since it calculated the load factors to develop the design equation such as to satisfy:

\[ \phi SSD_H \geq \alpha_V V_D \alpha_T T_D + \frac{\alpha_V^2 V_D^2}{\alpha_a a_{x,H/M}g} \]
The preliminary analysis indicates that at $\phi = 1$ for a truck on a wet pavement then, $\alpha_v = 1.18$, $\alpha_T = 2.0$, $\alpha_{a_x} = 0.48$ when the characteristic value is the observed mean.

This particular analysis may be extended as more knowledge is gained about the individual variables. For example, the deceleration rate of a truck is known to be an extremely complex interaction of many factors such that:

$$a_x = f(\text{location of centre of mass, wheelbase, driver skill, tire-road friction, temperature, etc.})$$

The analytical process easily accepts such complexities and should provide engineers with many unique insights into the design aspects of the problem.

4.2 Horizontal Radius of Curve

The driving on a super elevated horizontal curve may be thought of in terms of the driver-vehicle demanding some radius of turn, $R_{D/M}$ and that the highway supplied a radius of turn, $R_H$. Failure is defined as the radius of turn demanded by the driver-vehicle exceeding that supplied by the highway design. This is a very approximate set of criteria since in this example it is assumed that the vehicle rolls over and has no other mode of failure.

The radius of turn supplied by the highway is given as:

$$R_H = \frac{V_H^2}{e_H + f^H_y}$$

where

- $R_H = \text{radius of train of highway}$
- $e_H = \text{super elevation}$
- $f^H_y = \text{lateral friction factor}$

The expected demand for radius of turn by the driver $D$ and vehicle is:

$$E<R_{D/M}> = \frac{V_D^2}{a_y^M} + \frac{V_D^2 \sigma^2 a_y^M}{(a_y^M)^3} + \frac{\sigma^2 V_D}{a_y^M}$$

$$\text{Var}<R_{D/M}> = \frac{V_D^4 \sigma^2 a_y^M}{(a_y^M)^6} - \frac{4 V_D^2}{(a_y^M)^2} \sigma^2 V_D$$
and the limiting lateral acceleration for trucks is given by:

$$E <a_y^M> = \frac{T + h\theta}{h - T\theta} g + \frac{1}{(h - T\theta)^3} \left[ \theta (h - h\theta^2) \sigma_T^2 - (T + T\theta^2) \sigma_h^2 \right] + t \left( h^2\theta^2 \sigma_\theta^2 \right) g$$

[11]

$$\text{Var} <a_y^M> = \frac{\sigma_{a_y}^2}{\sigma_y^2} - \frac{1}{(h + T\theta)^3} \left[ \theta (h + h\theta^2)^2 \sigma_T^2 + (T + T\theta^2)^2 \sigma_\theta^2 \right] g^2$$

[12]

where

$$T = \text{half the truck's effective track width}$$

$$\theta = \text{super elevation of the curve}.$$  

Using approximate values for $a_y^M$, Navin (1991) has estimated that the probability that a fully loaded tractor trailer truck would exceed the available radius of turn due only to random chance is 1:100,000. The probability that a car meets a similar fate is remote.

This example assumes that the variables are random, normal and independent. These assumptions are only necessary to keep the mathematics to some reasonable level, the computerized analysis of SORM does not suffer such a constraint.

4.3 Road Side Barrier Impact

An interesting problem is specifying the reliability of a road side barrier. An initial review has been undertaken by Navin et al (1991). The occupant responds to the lateral acceleration, $a_y$, experienced by the vehicle during some suitable time interval. The barrier, on the other hand, must withstand an initial impact force which is the vehicle's lateral acceleration, $a_y$, and the mass of the vehicle, $m_v$. If the problem is then design a barrier for some force you may think of the vehicle as imposing a demand on the barrier which is $a_y m_v$ and the barrier supplying at the limit a force of $F_B$. If $a_y$ is calculated from the formula proposed by Olsen et al (1974) and that all the variables are random and independent, then the design equation becomes:

$$G(X_i) = F_B - \frac{V_c^2 \sin^2 \theta}{2g \left[ A \sin \theta - B \left( 1 - \cos \theta \right) + D \right]} m_v$$

[13]
where

\[ F_B = \text{specified barrier strength} \]
\[ v_0 = \text{vehicle forward speed at impact} \]
\[ \theta = \text{angle of impact} \]
\[ D = \text{barrier deflection} \]
\[ A = \text{distance front to CG of vehicle} \]
\[ B = \text{width of vehicle}. \]

The data used to obtain the mean and variance of each variable was compiled by Cooper (1980). The current population of automobiles as expected in 1990 has about 6.6 in \( 10^{-6} \) chance of exceeding \( F_B \) if the maximum design lateral acceleration is 15 g and the design vehicle weight is 2040 kg. The most likely highway conditions are: \( m_v = 1425 \text{ kg}, v_0 = 104 \text{ km/h}, \theta = 22^\circ, D = 0 \). The most sensitive variables in the equation are; mass, road-tire condition, and speed.

Another question is what is the probability that a vehicle as observed along a highway in 1975 would exceed the same force given similar random values except weight. The most likely design highway values are: \( m_v = 1870 \text{ kg}, v = 102 \text{ km/h}, \theta = 21^\circ \). The probability of exceeding the force is 2.4 in 10000. The results imply that, for passenger cars, barrier strength criterion was probably a little high for the fleet in 1975 and very high for the passenger car fleet of 1990 if the limits from structural engineering are employed.

5. FURTHER RESEARCH

This analysis has considered only random errors. It is possible to consider human errors but that must be done outside the computations as presented. Typically random errors cause only 20 percent of structural engineering failures, 80 percent are due to human error. Similar conditions probably exist in highway and traffic engineering, if police records of accidents are accepted as reasonably accurate.

The true meaning of the failure conditions, both the mode of failure and the probability of failure must be better understood. The mode of failure and corresponding sensitivity analysis may provide a method for road safety engineers to develop a preliminary priority list of variables to be brought under more stringent control. Similarly, it might help set limits as to what can be expected, particularly if real world failures can be firmly linked to the non-compliance derived by reliability analysis.

Ultimately there must be a firm link to risk assessment so the probability of failure irrespective of its source may be combined with the consequences. This will eventually require considerable input from public officials and practising engineers, but a first step may be taken by calibrating the existing highway geometry, operating codes and road side hazards.
6. CONCLUSIONS

The reliability based method presented in this paper is really a very general way of treating uncertainty in many civil engineering problems and appears to be very convenient for road safety problems. It is the mathematics of scenarios, or a quick way to do simulations.

Engineers are frequently required to forecast the future behaviour of a system. If the problem can be phrased as a demand for and supply of a unique measure and if that measure can be placed in a closed form mathematical solution, and if the variables in the equation have known Pearson type distribution, and non-compliance or failure is due to random events, then the reliability methods given in this paper can be employed. The method is useful even in cases where the majority of failures are due to human error since it does required the engineer to confront the possibility that the system may not perform up to expectation and the probability that such a non-performance will occur due to random events must be set by the engineer.

Using the ideas of load factors in the demand function, a performance factor for the supply function and an accepted level of non-performance as given by the Reliability Index forces the engineer-designer-analyst to more thoroughly explore the interaction of demand-supply-success. The same results may be obtained by scenario based calculations or simulations but the reliability based techniques are computationally more efficient. Finally, the design equations may be used to be calibrated values of $\alpha$ and $\phi$ so that societal and professionally accepted values of the Reliability Index may be estimated.

It seems appropriate that highway and traffic engineers should now apply reliability techniques more generally to all appropriate highway safety problems.
7. REFERENCES


NAVIN, F. 1990. Safety Factors for Road Design: Can They be Estimated? TRR 1280, Transportation Research Board.


Figure 1. Distribution of Demand and Supply for some Measurable Characteristic

Figure 2. Stopping Sight Distance Reliability Index vs. Performance Factor
\( (V_{\text{design}} = 80 \text{ km/h}, \ AB = AR = 1, \ SSD_M = 140 \text{ m}) \)
International Harmonization of Test and Evaluation
Procedures for Roadside Safety Features

Harry W Taylor
Office of Highway Safety
Federal Highway Administration
U S Department of Transportation
U S A
INTERNATIONAL HARMONIZATION
OF TEST AND EVALUATION PROCEDURES
FOR ROADSIDE SAFETY FEATURES
Harry W. Taylor
Office of Highway Safety
Federal Highway Administration
U.S. Department of Transportation

ABSTRACT

This paper summarizes the efforts of the United States Government to support international harmonization of test and evaluation procedures for roadside safety features. It also summarizes the proceedings of an international workshop on the International Harmonization of Test and Evaluation Procedures for Roadside Safety Features jointly sponsored by the Transportation Research Board Committee on Roadside Safety Features and the Federal Highway Administration. The workshop was held at the Annual Meeting of the Transportation Research Board on January 13, 1991. The workshop focused on identifying different test and evaluation procedures, the philosophies behind the procedures, and possible conflicts in procedures which prevent developing a common measurement system.

1. INTRODUCTION - CHAPTER 1

The United States is in the process of updating national test procedures and safety performance criteria for roadside safety devices such as guardrails, luminaire supports, and crash cushions. In order to advance the technology and achieve safer highways throughout the world, the Federal Highway Administration (FHWA) has proposed increased international cooperation in the development of roadside safety device testing and performance standards.

For many decades, the United States has developed roadside safety devices (furniture) to protect the occupants of errant vehicles that, for whatever reason, leave the road and strike a roadside obstruction. The United States began crash testing of these devices in the 1930's. However, guidelines were first developed for the testing of guardrails in 1962. The latest set of guidelines is contained in the National Cooperative Highway Research Program (NCHRP) Report 230, "Recommended Procedures for the Safety Performance Evaluation
of Highway Appurtenances," published in 1981. A committee of Federal, State, and university experts in this field are now in the process of updating these guidelines under the sponsorship of the Transportation Research Board.

According to Mr. Tom Heijer of the Netherlands at the September, 1989, international research and safety conference held here in Gothenburg, Sweden, different countries employ many dissimilar devices or designs to provide roadside protection. He went on to note that despite the dissimilarities, these devices perform their intended duties well, which is a credit to the research and design that went into them. FHWA believes that it is possible to develop a common measurement or translation procedure without necessarily abandoning national standards or impeding the development of new and better devices. FHWA is also convinced that international harmonization of performance criteria would benefit international trade and the exchange of ideas and technology between countries.

FHWA does not envision harmonization of test and evaluation procedures for roadside safety features as standardization. It is believed that standardization deals primarily with the definition of physical details of hardware. Harmonization, on the other hand, implies identifying the general performance characteristics of a device or features so that acceptable comparisons can be made. It implies a common measurement procedure or acceptable surrogates.

2. ACTION - CHAPTER 2

Concurrently with the efforts in the United States to update our test and evaluation procedures, it was understood that the European Committee for Standardization (CEN) was also preparing European standards for performance requirements and test methods for various safety road products, including safety fences and barriers, road signs, traffic signals, road and street lighting (performance requirements), and other traffic control devices. The goal of this effort is to provide for a unification of standards, regulations, certification, and testing to allow for the free flow of products and services among
all European Community (EC) and European Free Trade Association (EFTA) countries.

Because of the simultaneous development of procedures in both the USA and Europe, and in order to help advance international harmonization, the FHWA wrote to the heads of highway agencies of 54 different countries asking about their interest and support of international harmonization. They were also asked about their interest in a conference, to nominate a contact person, and on commenting on draft United States procedures and standards. Most of the replies from the countries were supportive.

In the fall of 1990, in parallel with the abovementioned efforts, FHWA wrote to various international bodies asking for their participation in the harmonization effort. It was suggested that it may be beneficial for the organizations to designate a committee or other group to aid in the coordination effort required.

The responses from the organizations were as follows:

a.) International Road Federation - Mr. M.W. Westerhuis, the Director General, said that it had already become apparent that the potential impact may well exceed the "constraints" of the EEC, and agreed that a representative of FHWA could attend meetings of their working group on safety fences and barriers.

b.) Permanent International Association of Road Congresses - Secretary General B. Fauveau recommended that a representative of FHWA meet with the PIARC Committee on Interurban Roads. As a result, the committee supported the formation of a subcommittee to address the issue. They suggested that the idea to form a committee be discussed by Dr. Larson, the FHWA Administrator, and Mr. Favenu in September at the PIARC Congress in Marrakesh.

c.) Organization for Economic Cooperation and Development - Mr Burkart Horn has submitted our request for a group to aid in the coordination efforts needed for better harmonization to the members of the OECD Steering Committee for Road Transport Research for their consideration.
d.) CEN Technical Committee 226, Working Group 1 - Representatives from the United States have contacted this group. FHWA has also contacted CEN in Brussels through the American National Standards Institute, USA, the official contact to the International Standards Organization. FHWA is still looking forward to communicating with CEN about international harmonization.

3. WORKSHOP - CHAPTER 3

Concurrently with our contact with the above-mentioned international organizations, the FHWA had proposed to the international highway community to hold an international conference (later changed to workshop) in the United States in 1991. Because of the support given our proposal and to follow up on the session held at this conference in 1989, a workshop was held January 13-14, 1991, at the Sheraton-Washington Hotel in Washington, D.C., USA. It was sponsored by the Transportation Research Board (TRB) Committee on Roadside Safety Features (A2A04) and the Federal Highway Administration.

The objective of the workshop was to assist in the development of a technical framework for the harmonization of test and evaluation procedures and standards for roadside safety hardware such as guardrails, sign supports, and crash cushions. It aimed to provide a forum to explore and identify common measurement procedures that may accommodate differences in philosophies among the countries involved.

The workshop was structured to explain the evolution of existing testing procedures and standards, to identify and discuss proposed procedures and standards, and to identify significant differences in conditions and philosophies.

The workshop approach was to discuss current and proposed testing procedures/performance standards for roadside safety devices, current harmonization efforts. We also discussed various existing national conditions, including traffic, such as size and weight of vehicles. We addressed possible impediments to international harmonization, and further coordinating efforts needed, such as establishing work groups through existing national and international organizations.
The structure of the workshop included three major components:

- **Invited Presentations.** Experts in test and evaluation procedures for roadside safety appurtenances (such as guardrails, bridge rails, and crash cushions) from the United States, Europe, and Australia were invited to make presentations at the workshop.

- **Workshop Groups.** These were formed to provide a forum for informal discussion on international harmonization. The attendees worked from prepared discussion topics which addressed many issues related to achieving harmonization of test and evaluation procedures.

- **Presentation of the Group Findings.** Breakout group leaders presented their summaries of the group findings and recommendations. Also, proposed actions to advance harmonization were discussed.

### 3.1 Workshop Summaries and Recommendations

The afternoon was devoted to Workshop Groups on several issues related to international harmonization of test and evaluation procedures. On Monday evening the Workshop Group Chairmen presented their summaries as part of the evening meeting of the Subcommittee A2A04(2) on International Research Activities. Each Workshop Group addressed a minimum of four basic topics.

### 3.3 Workshop Findings and Observations

The following discussion presents the more significant findings and observations which were generated by the Workshop Groups. They are categorized according to the major topics which were addressed by the workshops. There is considerable overlap in the findings:

**Critical Differences in Test and Evaluation Philosophies**

There are two different philosophies—testing for the average case, and testing for the practical worst case. In the USA, the practical worst-case approach is preferred over the typical or average
case, to avoid missing problems at either the low or high end. The average-case approach focuses on the largest number of accidents in an effort to make the greatest improvement in safety.

In evaluating crash test results, some Europeans measure quantitatively the passenger compartment deformation. In the USA, there is a passenger compartment intrusion criterion, but it is not quantified, so it is a judgment call.

The USA is moving toward testing with a 40-ton semi-trailer. However, a 30-ton single-unit truck may be more critical because it will produce a greater impact force.

Impediments to a Common Measurement Framework or Methods To Translate the Results for Comparison

The United States' use of English measurement systems in its procedures, while other nations' procedures are in metric, is not expected to be an impediment because the updated USA procedures will be changed to metric.

Specific National Conditions That May Affect Test and Evaluation Philosophies and Procedures

While there is considerable disparity in the vehicle fleets, traffic, and road conditions, there may be less disparity in the safety devices that are needed to handle these vehicles. It was stated that although you might not be able to pick a single condition, there may be a range of conditions that are probably representative of conditions internationally.

Pickup trucks (a small open truck) are used as test vehicles in the USA. However, up to 1.5 ton trucks are becoming common in Europe.

Differences in speed limits are a great source of lack of commonality. Speeds of 60 to 70 mph are common in Europe. Germany is expected to recommend a crash-test impact speed of 120 km/hr (73 mph).

Steps Needed to Increase Harmonization

In a general sense, there is substantial harmonization in existence. There is general
agreement that crash testing is the primary and decisive method of evaluating barriers.

More involvement among observers is needed in activities that develop test and evaluation procedures so interaction can take place and harmonization may be promoted.

The most likely harmonization of evaluation and crash-test criteria should be in procedures and reporting. It seems that if there is one thing that should be done, it is to agree on the information that ought to be reported on in crash-test results. If all the information from crash-test results would be available in a usable and accurately translatable format, it would go a long way in promoting harmonization. However, a test document that everyone uses as a standard can only be developed after additional discussions are held on the subject.

A Transportation Research Board circular documenting the workshops will be published in 1991.

4. CONCLUSION - CHAPTER 4

FHWA believes it is possible to develop a framework to compare roadside safety devices while still meeting various national conditions and needs, and still provide the necessary safety.
Occupant Risk by Different Severity Criteria

Vittorio Giavotto
Politecnico di Milano
Italy
OCCUPANT RISK BY DIFFERENT SEVERITY CRITERIA

Vittorio Giavotto
Dipartimento di Ingegneria Aerospaziale
Politecnico di Milano - Italy

ABSTRACT

In view of an international harmonization of highway safety standards, it is difficult to find an agreement on a single common severity criterion.

The paper report an investigation on the differences and the analogies of two among the most accepted criteria.

The research is carried on by means of simple models, and verified with 15 very reliable crash test data.

Interesting correlations are found, that may open the way to a better understanding of the problem and, hopefully, to the development of new findings.

INTRODUCTION

Severity criteria are related to the severity for the occupants of a vehicle in a collision; the evaluation of such severity is a very complex task, since it depends not only on the characteristics of the collision (as relative velocity, angle, mass and stiffness of the colliding objects), but also on more variable parameters, such as the age and the size of the occupants, the dimensions, the smoothness and the softness of vehicle interior, etc..

The idea behind Severity Criteria is to find a way to measure the severity in crash tests, which shall be objective and cheap enough to be adopted as a standard procedure to evaluate the safety performances of barriers and of crash cushions.

The most accepted criteria today are the Acceleration Severity Indices (ASI) and the Flail Space Criteria, both based on measures of vehicle motion (mostly accelerations).

In continental Europe Acceleration Severity Index has been used since a long time in crash test data processing, and experience has been consolidated on the base of such long usage. By comparing the values of

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the index with other measurable quantities, as vehicle interior deformation and anthropometric dummy motion, the index itself has been changed (by changing the constants in the formula) until a strong feeling has been reached that such ASI is a reliable criterion.

Analogous experience and feeling has developed about the Flail Space Criterion in United Kingdom and in United States, where the ASI is considered obsolete and non adequate.

For the sake of harmonization it will be interesting to understand how is it possible that very experienced laboratories have reached such apparently contrasting conclusions.

Even in Europe today it is very difficult to find an agreement on a single Severity Criterion, to be adopted as a common standard.

The aim of this work is to show, beyond the theoretical differences, that between the results of the two approaches there is a fair correlation, which can be both demonstrated theoretically and verified experimentally.

Hopefully this will contribute to reduce the dogmatism on both sides of the Channel, and to convince them the two criteria can be considered equivalent, provided the right parameter are selected.

It will be shown that a small change in a parameter, as e.g. the flail distance in OIV or a limit acceleration in ASI, may cause a variation in the results as large as changing from OIV to ASI.

ONE DEGREE OF FREEDOM

For the sake of simplicity it is convenient to start considering a motion in one direction, as it could be, approximately, an end on collision with a crash cushion.

In this case all points of the vehicle experience the acceleration $a = a(t)$, $t$ being time.

In the following $a(t)$ is considered to be the measure of this acceleration, pre-filtered, sampled and recorded in accordance with the International Standard ISO 6847-1980 (or the equivalent SAE J211a), frequency class CFC 60, minimum.

Acceleration Severity Index

In the single degree of freedom motion considered here, the Acceleration Severity AS is simply the absolute value of the average $\bar{a}(t)$ of $a(t)$, computed over a moving time interval $\delta$, and divided by the allowable $\bar{a}$ [1]. In other words:
\[ \ddot{a}(t) = \frac{1}{\delta} \int_{t-\delta/2}^{t+\delta/2} a(t) \, dt, \quad (1) \]

and

\[ \Delta S(t) = |\ddot{a}/\dot{a}| = (a/\dot{a})^{1/2}. \quad (2) \]

It can be easily demonstrated that (1) is in fact a low-pass filter with a cut-off frequency

\[ F = 1/(\pi \delta). \quad (3) \]

In fact if

\[ U(t) = A \cos(Ft/2\pi) \]

is a purely harmonic signal of frequency \( F \), it is easy to recognize that

\[ R(t) = \frac{1}{\delta} \int_{t-\delta/2}^{t+\delta/2} U(t) \, dt = U(t) \frac{\sin(F\pi \delta)}{F \pi \delta}; \]

it is quite evident that this is a filter having a gain \( G = \frac{\sin(F\pi \delta)}{F \pi \delta} \), as it may be observed in Figure 1, where such gain is plotted in dB, versus the product \( F \pi \delta \) in octave, and compared with the limits specified by the International Standard ISO 6847-1980 (or the equivalent SAE J211a).

It may be observed that it is not a very good filter, but it almost matches the standard for a filter having a cut-off frequency \( F \) defined by the condition

\[ F \pi \delta = 1, \text{ or } F = 1/\pi \delta. \]

The division of the allowable in (2) has the only meaning of reducing the allowable to unity.

Then ASI is basically the vehicle acceleration, low-pass filtered. If \( \delta = 0.05 \text{ s} \), as it commonly used, the cut-off frequency of such filter is approximately

\[ F = 6.4 \text{ Hz}. \]

The reason for such a low frequency is that, due to its relative softness, the contact of the occupant body to the vehicle acts as a mechanical low-pass filter, in transmitting vehicle transient motion to the occupant.
Figure 1 - Average over the interval δ as a low-pass filter

Then if \( \hat{a} \) is the allowable limit, for a collision to be considered safe, the absolute value of \( AS(t) \) shall not become more than unity, in all the collisions. In other words it must be that

\[
ASI = \max(AS(t)) \leq 1. \tag{4}
\]

The index ASI so defined can be assumed as a single measure of the severity of a collision.

**Flail Space Criterion**

The main objection to ASI is that it implicitly assumes that all the body of the occupant be continuously in contact with some part of the interior of the vehicle, non considering possible impacts, typically that of the head with the dashboard.

To evaluate the effects of these impacts the Flail Space Model considers the occupant (or typically its head) as a single rigid body, completely free moving while the vehicle is undergoing the acceleration \( a(t) \).

Assuming \( t = 0 \) at the start of the collision, in this single degree of freedom approach, the velocity \( V_r \) relative to the vehicle of the occupant, and the space \( S_r \) he has travelled respect to the vehicle, at time \( t \) are, respectively:
If $S^*$ is the available flail space, i.e. the original distance of the head from the dashboard, after a certain flight time $t^*$ there will be an impact of the head on the dashboard. The severity is related to the velocity of this impact, or to the Occupant Impact Velocity (OIV), that is

$$OIV = \int_0^{t^*} a(t)dt,$$  \quad (6)

where the flight time $t^*$ is found from the equation

$$S^* = \int_0^{t^*} V_r(t)dt.$$  \quad (7)

After the time $t^*$ the body representing the passenger, or its head, is assumed to remain continuously in contact with the vehicle interior, i.e. the impact is assumed as perfectly anelastic.

After that time the severity is related directly to the acceleration $a(t)$ of the vehicle, low-pass filtered to take into account the effect of contact softness. The maximum of this filtered acceleration, which is referred as Occupant Ridedown Acceleration (ORA) in US, and as Post Impact Deceleration (PHD) in UK, is compared with a limit safe value, in a way very similar to ASI (except the limit value and the filter frequency, which may be different).

The criterion is then twofold: within the acceptable limits it must be verified that \[2\]

$$\frac{OIV}{\dot{V}} \leq 1 \quad \text{and} \quad \frac{ORA}{\dot{a}} \leq 1$$  \quad (8)

The highest of the two ratios in the left hand side of inequalities (8) can be assumed as a single measure of the severity, with the Flail Space Criterion. In the following such measure will be referred to as the Flail Space Index (FSI), i.e.:

$$FSI = \max(OIV/\dot{V}, ORA/\dot{a}).$$  \quad (9)

CORRELATIONS

If for a certain collision $FSI = ORA/\dot{a}$, i.e. ridedown acceleration is more severe than impact velocity, the correlation of FSI with ASI should be straightforward, because they are basically the same thing, apart from differences in acceptable acceleration and in filter frequency.
On the contrary, the investigation for possible correlations of ASI with FSI is more interesting in the case where FSI = OIV/\bar{V}. In this case the vehicle acceleration after occupant impact is not so severe, and it seems reasonable to assume that the integration interval \( \delta \) of the maximum SI(\( t \)), i.e. of ASI, be more or less within the flight time \( t \).

With this assumption the expression (6) of the impact velocity can be put in the form

\[
OIV = \int_0^{t_1} a(t)dt + \int_{t_1}^{t_1+\delta} a(t)dt + \int_{t_1+\delta}^{t} a(t)dt, \tag{10}
\]

where \( t_1 \) is the start time of the interval \( \delta \) defined above.

From the definitions (1) and (4) it follows immediately that

\[
\int_{t_1}^{t_1+\delta} a(t)dt = ASI \delta \dot{\bar{a}}. \tag{11}
\]

The sum of the other two integrals on the right hand term of equation (10) can be expressed as the product of the sum of the integration intervals by a suitable average \( <a> \), i.e.:

\[
\int_0^{t_1} a(t)dt + \int_{t_1+\delta}^{t} a(t)dt = (t*- \delta)<a>; \tag{12}
\]

from the definition of ASI it follows that \( <a> \leq ASI \dot{\bar{a}} \); it can be put in the form

\[
<a> = \eta ASI \dot{\bar{a}}, \tag{13}
\]

where \( \eta \leq 1 \) is a non dimensional factor depending on the shape of the acceleration pulse in the flight time.

Taking into account (11), (12), and (13) the expression (10) of the impact velocity can be put in the form

\[
OIV = ASI \dot{\bar{a}} [\delta(1-\eta)+\eta t*]. \tag{14}
\]

In a similar way the integral in the definition (7) of the flight time can be expressed as the product of the interval \( t* \) by an average \( <V_r> \), and the average as the product of another shape factor \( \beta \) by the value OIV of \( V_r \) at the time \( t* \). Then

\[
S* = \int_0^{t*} V_r(t)dt = t*<V_r> = t*\beta OIV. \tag{15}
\]

Generally \( V_r \) is a increasing function of time, up to the maximum OIV, at time \( t* \). Then also the shape factor \( \beta \) is always less than unity; if the acceleration is constant during the flight time \( \beta = 0.5 \), if it is
increasing linearly from 0 \( \beta = 1/3 \); if the acceleration decreases prior to the time \( t^* \) \( \beta \) might even be slightly above 0.5.

From (15) the following estimate of the flight time can be obtained

\[
t^* = \frac{S^*}{\beta \text{OIV}}
\]  

(16)

which, by substitution in (14), gives eventually:

\[
\frac{\text{ASI}}{\text{OIV}} = \frac{1}{\delta \left[ 1 - \frac{\eta S^*}{\beta \text{OIV}} \right]}
\]

(17)

In the extreme cases \( \eta = 0 \), and \( \delta = \frac{S^*}{\beta \text{OIV}} = t^* \), from (17) comes that the correlation between ASI and OIV is very strict, because

\[
\delta \text{ASI} = \text{OIV}
\]

(18)

The first case, \( \eta = 0 \), is the case where the acceleration pulse has a duration shorter than \( \delta \), and so there is no sensible acceleration outside the interval \( \delta \). This is verified by brief collisions, as usually are the side impacts of small private cars against relatively stiff barriers. It is worth noting that collisions of small cars are very important, being the ones used to assess the safety performances of barriers, on both sides of the Atlantic.

In the case of crash cushions, where the duration of the collision must be longer, the condition \( \delta = t^* \) could be used to find an optimum value of \( \delta \), to obtain the best possible correlation of ASI with OIV.

Given the limit values of ASI and OIV, from (17) the value of \( \delta \) needed to obtain these two values from an acceleration history is

\[
\delta = \frac{1}{(1 - \eta)} \left[ \frac{\text{OIV}}{\Delta \text{ASI}} + \frac{\eta S^*}{\beta \text{OIV}} \right]
\]

(19)

For a longitudinal impact against a crash cushion the recommended limits are \( \text{OIV} = 9 \text{ m/s} \) [4] and \( \Delta a = 12 \text{ m/s}^2 \); moreover the second shape factor \( \beta \) is likely to be near to 0.5, because the cushion deflection must be very large, and consequently the reaction force must last a relatively long time.
Figure 2 - Best δ for Crash Cushions  

Figure 2 shows the trend, versus the shape factor $\eta$, of the values of $\delta$ computed with (19), for crash cushion collisions near to the acceptable severity limit. The values of the averaging interval $\delta$ in Figure 2 allow to obtain $ASI = 1$ in collisions giving $OIV = 9m/s$, when $\delta_x = 12m/s^2$, $S*x = 0.35m$, $\beta = 0.4, 0.45, \text{and} 0.50$.

The best value in this case is $\delta = 0.076s$; the variation with the shape factors $\eta$ and $\beta$ is not very large, particularly if $\eta$ is not very large.

For a side collision against a barrier the acceptable limits are $OIV = 6m/s$ and $\delta_y = 9m/s^2$; the values of $\eta$ should be relatively small, while the values of $\beta$ might be slightly larger.

Figure 3 shows the values of $\delta$ which give $ASI = 1$ in collisions against barriers with $OIV = 6m/s$, when $\delta_y = 9m/s^2$, $S*y = 0.25m$, $\beta = 0.4, 0.5 \text{ and } 0.6$, for a variation of $\eta$ from 0 to 0.3.

The best value is $\delta = 0.0675s$, and again the variation with the shape factors is not very large.

Figures 4 and 5 show the values of $\Delta SI$, computed by means of (17), with the parameters assumed above for crash cushions and for barriers, and, respectively, $\delta = 0.076s$ and $\delta = 0.067s$.

In both cases the variations of $ASI$ from unity are moderate.

It must be noted that Figures 2 to 5 pertain to correlation of $ASI$ and $OIV$ in the vicinity of the limit condition. If these parameters must be adopted in acceptance criteria such correlation should be the more important.
MULTIPLE DEGREES OF FREEDOM

In general all the 6 degrees of freedom of vehicle rigid motion participate to the movement in a collision.

In this case the complete expression of AS(t) is more complex, taking into account the interaction of the 3 components of the acceleration of a given point (usually the center of mass, or the occupant position) of the vehicle.

If $\ddot{a}_x(t)$, $\ddot{a}_y(t)$ and $\ddot{a}_z(t)$ are the 3 components, along vehicle axes, of the acceleration of the given point, and $\dddot{a}_x$, $\dddot{a}_y$ and $\dddot{a}_z$ are the relevant acceptable accelerations:

$$AS(t) = \left[ \left( \frac{\dddot{a}_x}{\ddot{a}_x} \right)^2 + \left( \frac{\dddot{a}_y}{\ddot{a}_y} \right)^2 + \left( \frac{\dddot{a}_z}{\ddot{a}_z} \right)^2 \right]^{1/2}. \quad (20)$$

In Europe (France, Germany and Nederland), for passengers wearing safety belts, the generally used limit accelerations are:

$$\dddot{a}_x = 12g, \quad \dddot{a}_y = 9g, \quad \dddot{a}_z = 10g.$$

Again AS(t) or its maximum value ASI must be less than unity. This means that the modulus of the averaged acceleration must remain within an ellipsoid, solid with the vehicle, whose semi-axes are, respectively, $\ddot{a}_x$, $\ddot{a}_y$ and $\ddot{a}_z$. It is the simplest possible interaction model of 3 mutually orthogonal quantities.
The OIV/ORA criterion changes in the sense that OIV and ORA are evaluated separately in the x and in the y direction, and compared with the relevant acceptable values.

In successful collisions against a barriers or crash cushions there is one component of the acceleration which is largely dominating; then the results of the single degree of freedom approach remains approximately valid even when more degrees of freedom are considered.

The THIV/PHD criterion developed in UK [3] is different from the OIV/ORA only because it takes into consideration the effect of yaw; even this last effect, in the order of approximation of the present study, can be disregarded.

EXPERIMENTAL VERIFICATION

Experimental data for this verification are taken from 15 full scale crash test performed at TNO Delft, between November 1988 and December 1989. Such tests are part of a wide research program sponsored by SINA Milan, having the aim of improving the know how in barrier design.

Tests were conducted with two vehicle types, i.e. Fiat UNO (12 tests), and Fiat REGATA (3 tests). Four test couples (89141 and 89142, 89143 and 89144, 89151 and 89152, 89431 and 89432) had nominally identical vehicle, impact velocity and angle, to check possible scatter in results.

All the tests were done against New Jersey Type concrete barrier, except tests n. 89431 and 89432 that were against the SINA deformable steel barrier.

In many of these tests two Hybrid II dummies were installed in the front seats.

The accelerations recorded during the tests (12 from the vehicle and 18 from the dummies), sampled at the frequency of 8 kHz, have been digitally stored in diskettes, which are still available.

Vehicle accelerations, digitally filtered to CFC 60, have been used to compute, at each time instant, the three components of the linear acceleration, the three of the angular acceleration, and the three of the angular velocity, in vehicle frame. From these the acceleration of any point connected to the vehicle can be easily computed at any time, and the complete motion of the vehicle could be reconstructed by integration.
Table I - OIV, THIV, ASI from Experiments

<table>
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<tr>
<th>TEST n.</th>
<th>Impact Velocity [km/h]</th>
<th>Impact Angle [*]</th>
<th>Vehicle Mass [kg]</th>
<th>OIV</th>
<th>THIV</th>
<th>ASI δ=50ms</th>
<th>ASI δ=70ms</th>
<th>ASI δ=90ms</th>
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</table>

† non including the mass of 2 dummies

* impact against deformable steel barrier

Table I shows the 15 tests, together with OIV(lateral) and ASI, all computed from a tri-axial acceleration meter installed in the center plane of vehicle, on the tunnel, close to the gear lever. OIV (lateral) has been computed assuming conventionally the lateral flail distance $S_y = 25$ cm.

ASI has been computed using 3 different value of the averaging interval $\delta$, i.e. the usual 50, 70 and 90 ms.

Figure 6 shows the correlation, which is quite good, with an exponent of .625, not far from what was expected from theory. It is worth noting that the limit value 1 of ASI corresponds to OIV = 5.095 m/s = 16.71 fps.
The comparison of the values in the last three columns of table I shows that increasing the averaging time interval \( \delta \) the value of \( \text{ASI} \) decreases slightly. It is worth noting that averaging accelerations over an interval \( \delta \) of 70 ms the limit value \( \text{ASI}=1 \) is correlated with \( \text{OIV} = 5.98 \text{ m/s} \), very close to the limit value of 20 fps recommended by Report 230.

Figure 6, 7 and 8 show how the correlation improves and the exponent tends to unity, when the time interval \( \delta \) approaches \( t^* \), that from the head acceleration recordings appear to be close to 90 ms. This confirms the theoretical expectations.

It may be worth noting how the two points corresponding to steel deformable barriers, which are relatively apart from the best fit curve in fig. 6, come closer and closer in figs. 7 and 8, when \( \delta \) increases.

Table I reports also the values of \( \text{THIV} \).

The computation of \( \text{THIV} \) has been carried on following the recommended procedure, i.e. considering only the motion in a horizontal plane; yaw rate has been obtained from the 12 accelerations measured, with the procedure mentioned above.

In Figure 9 the correlation seems to be fairly good, as was already found by L.Laker [3].
CONCLUSIONS

The tests considered are only 15 side impact tests. But they cover a relatively wide range of speed and angle, two different vehicles, and two very different barriers; and, what's more, they are complete and reliable.

For side impacts it seems that ASI and OIV (or THIV) have a sound correlation which can be explained theoretically and verified experimentally. The two criteria are practically equivalent and each choice could be a good one. A further verification with more experimental data will strengthen this conclusion.

For frontal collisions against crash cushions the theory suggests a similar conclusion; but unfortunately the experimental verification could not be carried on for the lack of reliable data. If possible it will be done in the future.

In any case correlation between Acceleration Severity Indices and Flail Space Criteria seems to be possible.

More experience and more data are needed to draw a firm conclusion on a possible single common choice, but hopefully this work may help in understanding the meaning and the correlation between the different criteria.

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Hayes E Ross, Jr
Texas Transportation Institute
Texas A&M University
USA
ABSTRACT

"PROPOSED GUIDELINES FOR TESTING AND EVALUATING ROADSIDE SAFETY FEATURES - AN UPDATE TO NCHRP REPORT 230"

by

Hayes E. Ross, Jr.
Texas Transportation Institute
Texas A&M University
College Station, Texas USA

NCHRP Report 230, "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," published in March 1981, contains recommended procedures for evaluating the safety performance of highway features. These recommendations were based on a synthesis of information found in the literature and a state-of-the-art survey, and on advice obtained from a selected group of acknowledged experts. Since its publication, NCHRP Report 230 has served as the generally accepted guide for developing and evaluating highway safety hardware, not only in the USA but in other countries as well. However, the mix and characteristics of highway vehicles have changed substantially since 1981; safety features not considered in that report have come into use, and research efforts using full-scale crash tests, bogie and pendulum tests, computer simulations, and traffic accident analyses have resulted in improved understanding of vehicle interactions with highway features, including roadside terrain. In addition, performance levels other than those included in NCHRP Report 230 are being considered for use. On the basis of these changes, an update of NCHRP Report 230 is needed at this time to ensure continued improvement in the level of safety provided users of the highway system.

Therefore, the object of the update is promulgate recommended procedures for the safety performance evaluation of both temporary and permanent highway features in such a manner as to reflect advances in technology and to accommodate current and anticipated roadway and vehicle characteristics.

This presentation will discuss the status of the update, including the major changes being proposed. It is noted that he second draft of the update was released for review July, 1991. Plans call for a national and international review of this draft by experts in roadside safety design. It is anticipated that the final report will be completed in early 1992.
Status of the European Work on Harmonizing Requirements and Test Procedures for Roadside Safety Features

Jacques Boussuge
SETRA
France
STATUS OF THE EUROPEAN WORK ON HARMONIZING REQUIREMENTS AND TEST PROCEDURES FOR ROADSIDE SAFETY FEATURES

Jacques BOUSSUGE

SETRA (France)

The European Committee for Standardization (CEN) has decided in 1990 to initiate a standardization programm in the field of the road equipment. For this purpose, a technical committee has been created - the TC 226. On the occasion of its first meeting in April 1990, the TC 226 has entrusted the Working Group 1 with the standardization of safety barriers, crash cushions and, in a general way, of road restraint systems.

This contribution is aimed in the beginning at recalling the European objective and then at summing up the work already completed by the WG1 after one year of activity.

1. EUROPEAN OBJECTIVES:

ROAD SAFETY AND THE INTERNAL MARKET IN 1993

As you certainly know, the accidental exits from the carriageway is one of the major factors of road accidents: 25 to 40 percent of all the accidents, according to the type of road. The answer and the solution to this safety problem consists in removing dangerous obstacles - when it is possible! — and in implementing road vehicle restraint systems between the carriageway and the obstacle, or of the change of level.

Because of the complex aspects of the road accidents, most of the national road administrations have since long carried out their own safety studies. This has led the authorities to require devices whose design and, as a consequence, manufacturing differ from one country to another; different provisions are therefore provided for in the national regulations.

In the opinion of the EEC, such nonuniform regulations do but install technical hindrances to the trade, that should now be removed in order to achieve the European internal market in 1993. For this purpose, the CEN could be mandated to harmonize the technical specifications that shall eventually become compulsory national regulations.

The CEN has the advantage of grouping together not only the 12 states of the EEC but also the 6 states of the EFTA - European Free Trade Association.
As a consequence, industries, administrations and research laboratories of these 18 states have already begun with the standardization process in the framework of the CEN. The first aim of this international activity consists in achieving the objectives on which the completion of the Single European Market depends.

2. BASIS OF STANDARDIZATION

As concerns the roadside devices, it has been unanimously agreed upon taking as basis for the standards their satisfactory behaviour under impact tests. Within the short time fixed by the CEN, this appears to be the criterion on which a consensus may be reasonably reached.

By harmonizing the performances with several levels, the standards could possibly foster the innovation. The industries are thus free to design products as far as they meet the conditions of the standard performances, while using various materials such as metal, concrete, plastic or wood. But the standards also remain open to include other devices with complementary functions, such as noise protection, pedestrian restraint or aesthetic aspects.

3. WORK OF THE TC 226/WG1

The Working Group 1 is composed of 35 experts from 14 countries.

The object of the CEN/TC/226/WG1 consists in dealing with all the restraint systems used on central reserves of motorways and on verges of roads, including bridge or retaining wall structures for permanent and temporary use, with priority being given to the road vehicle restraint systems that are the most used devices.

The work that began one year ago, has consisted in gathering the test conditions either applied in the research laboratories or provided for in the national regulations in force in 1990. The figure hereafter presents various test conditions.
TEST CONDITIONS IN EUROPE
1990 - SITUATION
TESTING CHARACTERISTICS

SAFETY BARRIERS
F 100 : STATE / SPEED KM / H

CRASH CUSHIONS

VTI RAPPORT 372A
4. THE CHOICE OF PERFORMANCES

The future systems to be agreed upon on the market should meet the various and complex needs of the road design.

In a general way, the choice of a suitable safety barrier depends on the risk to be covered and the risk is a function of the road and traffic characteristics as well as of the nature of the obstacles or of the vicinity.

The WG1 has chosen a classification based on the restraint capacity. The normal level of restraint capacity concerns the containment of light vehicles, the high level concerns that of the current lorries and buses and the very high that of the heaviest authorized lorries, i.e. near to 40t.

The tests for all the containment levels are specified in terms of impact speed and angle, mass and dimensions of the colliding vehicle.

5. ACCEPTANCE CRITERIA

The principal acceptance criteria for these tests are as follows:

1. Behaviour of the vehicle:
   - the vehicle shall not breach the barrier
   - the vehicle shall be redirected.

2. Behaviour of the barrier:
   - No major part of the barrier shall fracture and become detached.

3. Severity index

   Both the Acceleration Severity Index (ASI) and the Theoretical Head Impact Velocity (THIV) will be used before reaching any agreement upon a single index.

4. Vehicle deformation

   The deformation of the vehicle interior shall be evaluated by filling the form of the Vehicle Interior Deformation Index (VIDI).

   Generally, these criteria may not be evaluated on only one representative test. They may be not critical under the same impact conditions. In particular, a high containment level system that can meet the conditions of restraint for lorries, might not meet the correct performance for the impact severity required for a light vehicle.
It has therefore been decided to carry out two impact tests for one specified performance class:

- one test for checking mainly the maximum containment level, and
- an additional test on a small passenger car for checking the behaviour of the vehicle and the impact severity for the safety of the occupants.

The final figures are not yet ready. To determine them, our attention is now focused on the necessity of being coherent with the development of the types of vehicles that will run in the future years, without going too far from the previous conditions. A majority of existing systems should easily find their place in the new scheme.

6. CONCLUSION

This is the present stage of reflection of our WG1. The European harmonization must obviously go further namely as concerns the end of performance standards for the safety barrier, crash cushions and pedestrian guardrails. However, the standardization in this field might be more difficult and ask for more time as we expected.

May I add, in conclusion, that a standard is never technically definite and that it is it's proper vocation to be revised one day or another. And perhaps, will the mondial market be our objective for the next time.
Development of a Methodology for Measuring Improper Seat Belt Use

Brian A Grant
Head, Human Factors Section
Transport Canada
Canada

Jocelyn B Pedder
Vice President
BioKinetics & Associates Limited
Canada

and

Nicholas Schewchenko
Project Engineer
BioKinetics & Associates Limited
Canada
1. INTRODUCTION

Seat belts are one of the most effective safety features available in motor vehicles today. However, to be effective they must be used and they must be used properly. Recent efforts in Canada have produced a national seat belt wearing rate of 82%, with some regions having wearing rates over 90% (Transport Canada, 1991). Other countries have achieved similar wearing rates. While considerable effort has been made to increase the use of seat belts, relatively little effort has been directed at determining whether they are used properly.

Improper use of seat belts may occur because of poor seat belt design or improper adjustment. Poor seat belt design makes it difficult for vehicle occupants to adjust the belt to fit properly, or encourages users to use the seat belt improperly. Improper adjustment results from a lack of knowledge about how to use a seat belt properly or from specific efforts to use the seat belt in an improper manner. Examples of the latter include introducing excessive slack or wearing the shoulder belt under the arm. Either type of improper use may reduce the effectiveness of the seat belt and in some cases may produce injuries from the belt itself.

Studies, reviewed below, indicate that the frequency of improper use of seat belts is a problem, and that improperly adjusted seat belts can produce injuries to vehicle occupants.

1.1 Frequency of Improper Use

Torrington and Hull (1981) report data on seat belt wearing rates and adjustment collected at the roadside in New Zealand from 1974 to 1979 when only 20% to 30% of seat belt systems were equipped with inertia reel retractors. Given that less than 5 cm of slack was considered acceptable they showed that less than 40% of the seat belts in the surveys were adjusted properly. Females were slightly more likely to have improperly adjusted seat belts than males while children were found to most frequently have excess slack in the seat belt.

Oranen and Koivurova (1980) report on a roadside seat belt survey in Finland in 1978 when the seat wearing rate was approximately 72%. Data were collected on both urban streets (50 km/h) and highways (80-100 kph). In addition to checking the mechanical integrity of the seat belt systems, belts were checked to determine if they were twisted or too slack (more than the thickness of a flat hand, or 4 to 5 cm). For belts with automatic retractors, 26% were twisted and 1% had excessive slack.

The views expressed in this paper are those of the authors and not necessarily those of Transport Canada or Biokinetics and Associates Limited.
slack. Male drivers, and older drivers were more likely to have seat belts without any problems.

Booth (1988) observed vehicles at shopping centres in Sydney, Australia, to determine the seat belt use rate, and the rate of improper use. During the survey 3200 vehicles were observed, and 4213 adults had seat belts available to them. The wearing rate was 90%, with 91% of vehicles having inertia reel belts. Improper use was 3.9% with the majority of improper use the result of excess slack in manually adjusted belts. A small percentage of occupants, less than 1% in total, had twisted belts (.14%), belts worn under the arm (.14%) or had the belt just sitting on the shoulder without being fastened (.55%).

Improper use data for the United States are presented by Bowman and Rounds (1989). Their data, on three types of misuse, are taken from the 19 city survey of belt use; an annual survey conducted to monitor the seat belt wearing rate. Of the nearly 40,000 observations of shoulder belt use 1.8% of drivers were wearing the shoulder belt under the arm, 0.3% had the shoulder belt behind the back, and 1.1% have excessive slack in the belt. The misuse rate is reported to be slightly higher for females than male, with females most likely to wear the shoulder belt under the arm.

Depending on the definition of improper use these studies report between 60% and 3.2% misuse of shoulder belts. The upper number is probably the result of a high percentage of manual belts in the vehicles observed. If we assume that a twisted belt does not seriously affect seat belt performance the percentage of misuse of shoulder belts can probably be estimated at between 3% and 4%, with females having a slightly higher misuse rate than males. No data are available to estimate the improper use of lap belts.

1.2 Effects of Misuse

Data from a number of studies using in-depth analysis of automobile accidents (Dance et al. 1981; Danner et al. 1984; Gallup et al. 1982; Green et al. 1986; Green et al. 1987a; Green et al. 1987b) indicate that serious, and often fatal injuries occur when the seat belt contacts the soft abdominal area during a collision. Contact with the abdominal area occurs when the lap belt is worn too high on the hips. Appel et al. (1978) also concludes that excess slack in the lap belt may lead to seat belt induced injuries.

Excessive shoulder belt slack has been identified as a contributing factor in causing fatalities in a number of studies (Appel et al. 1978; Costa and Robbs 1988; Danner et al. 1984). Unfortunately the amount of slack in the shoulder belt present at the time of the collision is not well documented. Analyses of accidents in which the occupant wore the shoulder belt under the arm have shown that this type of misuse can contribute to injuries and death (Green et al 1987; States et al 1987)

1.3 Summary

Research indicates that improper use of seat belts occurs with sufficient frequency to be of concern, but the accuracy of the estimates is not well established. Given the potential for injuries resulting from the improper use of seat belts it is important that good estimates of misuse be developed.
The purpose of this study is to develop a methodology for measuring the improper use of seat belts. The methodology must provide reliable and valid measures of improper use. It must be relatively easy to use and must lend itself to the collection of large amounts of data. A large sample of observation will be needed to get a reasonable sample of the estimated 5% of cases with improper use, as identified above.

The study is divided into two phases, methodology development and field trials. During the methodology development phase a variety of methods for measuring improper fit were reviewed. In particular, some measurement techniques which could produce exact quantitative measures were reviewed as well as those that would produce less precise estimates. This part of the report describes the process used to select the methodology which was tested in the field study. The field study provides an evaluation of the selected methods and provides estimates of the level of improper use of seat belts. A general discussion of the methodology selected and the results is presented in the final section of the paper.

2. METHODOLOGY DEVELOPMENT

The focus of the study was narrowed by concentrating on measuring the improper use of seat belts by drivers only. Because some of the methodologies to be tested would rely on visual recognition of misuse it was also decided to conduct the initial work on vehicles with only the driver present. This made it easier for observers and recording systems to see all the necessary components of the seat belt assembly without sight lines being blocked by other occupants. In addition, it eliminated the need to collect multiple observations from one vehicle which would have been difficult for on-site observers.

2.1 Types of Misuse and Viewing Area

Preliminary observations were conducted to determine the types of misuse which could be expected in the field and to determine the viewing area required to observe each misuse type. The results of these observations are presented in Table 1, and the information was used in the placement of observers and cameras throughout the study.

2.2 Methods Considered

The different methods of collecting improper use data which were considered are presented in Table 2. The methods reviewed were divided into two broad categories, intrusive and nonintrusive. Intrusive methods are those which require the driver of the vehicle to stop, and allow measurements to be taken of the position of the seat belt. Nonintrusive methods are those which do not require cooperation from drivers, and therefore do not impede their travel.

2.2.1 Intrusive methods

Intrusive methodologies which were considered included simple measurement of seat belt position on the individual using rulers and calipers, digitizing the position...
of the belt and the subject relative to the interior of the vehicle using a sonic digitizer, stereo photogrammetry, and laser scanning. Each of these methods would provide precise data from physical measurements. They also require active cooperation from subjects and require considerable time to collect and analyze. In field use they would require the presence of police officers to direct traffic into the test area.

Table 1: Required Viewing Areas for Monitoring Seat Belt Misuse

<table>
<thead>
<tr>
<th>Misuse Type</th>
<th>Shoulder Belt</th>
<th>Lap Belt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outboard</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>Shoulder</td>
<td>Torso</td>
</tr>
<tr>
<td>No belt</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Std. belt position</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Slack in shoulder</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Slack in lap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder belt under arm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder belt behind back</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twist in shoulder belt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twist in lap belt</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>High lap belt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sitting on belt</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Shoulder belt off shoulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder belt on neck</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Table adapted from Biokinetics (1991a)

Sonic digitizing, stereo photogrammetry and laser scanning provide a permanent record of the belt system layout allowing for further analyses at a later time. However, these systems are sensitive to environmental conditions, that is, they have to be used in areas where environmental conditions (temperature, humidity, wind, etc) are relatively constant. In addition, they have relatively high capital costs and require well trained operators to use them correctly.

Measurement of belt position on the individual using rulers and calipers requires less time to collect the data than the other methods. Capital costs are negligible and operator training is minimal.
2.2.2 Nonintrusive methods

Nonintrusive methods can be divided into two groups, those which use direct human observation and those which record an image of the scene for later analysis. Image recording systems can be further subdivided into those which use film and those which use video tape as the recording medium.

2.2.2.1 Direct Observations

Direct observations are defined as those collected by an observer at the roadside. Direct observations have the advantage that observers can work in relatively low light levels, once the data are collected they can be analyzed, (unlike image recording system for which the images must be reviewed after they have been collected), the setup is relatively simple, there are few restrictions on sites, and therefore it is possible to collect data from many different sites. Direct observation methods only allow the observer to see the seat belt from one angle, but do allow minor changes in viewing angle to reduce the effects of glare and to resolve inconsistencies in what is observed. Observers have only a limited amount of time to collect the data, basically the amount of time a vehicle is stopped, which can vary from a few seconds at a stop sign to 30 to 40 seconds if a traffic light controlled intersection is used. There is no visual record of the scene made so it is not possible to recheck the data or to collect additional information if it is required.
2.2.2.2 Image recording

Image recording systems provide a permanent record of the observations, they allow the observer more time to review the data, and they allow for the review of images taken from different angles. It was anticipated that these features would improve the accuracy of data derived from image recording systems. Options for image recording systems include photography using film and video systems using video tape as the recording medium. Tests were conducted to determine the quality of output that could be achieved with both systems. Each system was tested using black and white, colour and infrared recording systems.

The image recording systems were evaluated in terms of their light sensitivity, ability to record tonal variations in the image, accuracy or resolving power, imaging speed, data collection rate, general operating requirements and conditions, and relative costs. They were tested in a laboratory setting and in limited field tests to determine their capabilities. The required viewing angles (Table 1) made it necessary to use three cameras; one providing a view from the driver's side, one providing a view from the passenger side, and one mounted overhead to provide a view of the front torso area. Tests were conducted at a variety of ambient light levels, but light levels within the vehicle were generally low. Adding external light sources to increase lighting levels within the vehicle would have been distracting for drivers.

The major problems for all image recording systems are low light levels, reflected glare from vehicle windows and the fixed viewing angles for cameras. In the most serious cases, lack of light or glare, it is impossible to see inside the vehicle while in other cases they reduce contrast making observation very difficult. The effects of glare varies throughout the day depending on the position of the sun and the presence of clouds. The worst conditions for glare occur with overcast skys, but bright ambient light.

Image recording systems are also complicated to set up requiring the cameras be interconnected so multiple images can be recorded, and they must be mounted on stable structures. The problems associated with system setup reduces the number of sites at which data can be collected. However, once the system is in place it can collect images at the rate of traffic flow thereby ensuring a large number of observations are collected.

Finally, image recording systems require that the data be reviewed in detail after it is collected. There is, therefore, additional time involved in getting each observation ready for analysis. However, because time constraints on extracting the data are not present it is possible to ensure observers are functioning at an optimum level by providing frequent breaks.

**Photographic systems.** Photographic systems provide the best resolving power, but produce poor results in low light conditions, and slow imaging times make them less acceptable for recording moving vehicles, even with fast film. Colour film produces images which are of the same resolution as black and white film, but provide better tonal discrimination which make it easier to see light coloured seat belts on light clothing and dark coloured belts on dark clothing. Infrared images are seriously affected by glare. Although the initial costs for photographic cameras is lower than for a video system the costs of processing film makes video a more cost effective system. An added problem with the photographic system is triggering the shutters at the exact time required to capture the image, and this
point varies with the three different camera angles. In addition, there are problems coordinating the three images for viewing in the data extraction phase.

**Video systems.** Video systems provided less resolving power than photography, but are more effective in low light. Although colour video provides colour cues for discriminating clothing from the seat belt, the colour is lost at the low light levels found inside the vehicle. Tests with an infrared camera, which would have allowed for data collection at night, indicated that it was more susceptible to glare from the vehicle windows than the other cameras. The best results were obtained with the black and white cameras which provide acceptable resolution, work effectively in all light levels, are compact, and provide good tonal variations for distinguishing the seat belt from clothing.

Video cameras and recording systems eliminate problems of triggering the devices as they can be left on to provide a continuous record of all vehicles as they pass the data collection point. Coordination of the video images was initially a problem because three video recorders were being used, but the use of an automatic switcher made it possible to record images from each of the cameras sequentially on one video tape.

Images were recorded using a Super VHS video recorder and Super VHS tape. These provide the highest resolution possible without the need to use broadcast quality equipment. The system also allows for frame by frame viewing of high quality images, and provides time and date stamps, for the images collected, making it possible to move quickly, within a tape, to find a specific observation.

### 2.3 Discussion

After reviewing the various potential methodologies it was decided to eliminate the intrusive measurement techniques from further study for two main reasons. First, it was concluded that although the intrusive techniques would provide useful and highly accurate data they would be less likely to yield valid results because of the likelihood of drivers changing their seating position, and possibly adjusting their seat belts when stopped. Secondly, the methodology had to be capable of collecting a large quantity of observations, between 10,000 and 20,000, and it was concluded that the intrusive methods would be extremely costly for a survey of this size. In addition, the restrictions associated with their use (for example, finding suitable locations, the need for police cooperation etc.), the field makes them less desirable than the other nonintrusive methods.

Therefore, it was decided to conduct further development of the nonintrusive methods. In particular, the use of black and white video recording and direct observations collected at the roadside were selected for further development and testing in the field study.
3. FIELD STUDY

3.1. Introduction

The field study had two main purposes: to further develop and evaluate the two test methodologies (video recording and direct observation) and to obtain an estimate of the level of seat belt misuse. In evaluating the methodologies it was important to determine if one method was more accurate than the other and which method would provide the best data in a large scale study. Estimating the level of misuse would provide information on the need and potential value of conducting a large scale study.

To evaluate the methodologies, in terms of accuracy of data collection, it was necessary to know the exact type of misuse from a sample of vehicles. This was accomplished by using a group of drivers and vehicles in which the misuse type was introduced as part of the research, these observations are referred to as target vehicle observations.

3.2. Method

3.2.1 Location and Sample

The seat belt data were collected at a T intersection controlled by 3-way stop signs. The layout of the intersection is presented in Figure 1. Traffic volume was generally over 100 vehicles per hour at the observation point which was on the cross bar of the T; vehicles either proceeded straight ahead or turned left. The vehicles were stopped at the intersection just long enough to allow recording of the seat belt use information. Data were collected over two days, from 10:00 to 13:00, and from 14:30 to 19:00 during July so ambient lighting was good throughout the data collection period. The street was in an area of mixed residential and light industry.

Data from approximately 300 target vehicles (those in which the seat belt misuse was known) and 300 non-target vehicles were recorded by the observers. The video system recorded observation on approximately 3000 usable observations, of which the first 1000 were used in the current study. Usable observations consisted of passenger cars and light trucks with the driver as the only occupant, and which could be seen by the video cameras. The later requirement eliminated a number of light trucks and most commercial vehicles. The non-target group consisted of 68% males, 18% under 25 years of age, 61% between 25 and 50 years old, and 20% over 50 years old. Estimates of car size indicated that 29% were compact, 30% were mid-sized, and 41% were large size.

3.2.2 Equipment and Setup

3.2.2.1 Video

The locations and mounting heights of the three video cameras (Panasonic BD404, 25mm lens; Panasonic BL600. 150mm lens; Panasonic BD400, 75mm lens) are
shown in Figure 1. The cameras provided views of the driver's side, passenger side, and the front of the vehicle. The two side view cameras were mounted slightly above the line of sight and aimed down to provide a view inside the vehicle. The front view camera was mounted 4.9 metres above the road surface.

![Diagram of camera positions and coordinates](image)

<table>
<thead>
<tr>
<th>Camera</th>
<th>Coordinates (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>X: 5.3, Y: 1.4, Z: 2.1</td>
</tr>
<tr>
<td>#2</td>
<td>X: 9.1, Y: 6.2, Z: 1.8</td>
</tr>
<tr>
<td>#3</td>
<td>X: 5.3, Y: 5.3, Z: 4.9</td>
</tr>
</tbody>
</table>

Figure 1: Layout of observation site and camera positions (observers stood at camera positions 1 and 2) [from Biokinetics, 1991b]

The cameras were linked by overhead wires to an automatic switcher which also provided synchronization pulse for cameras (Genlock). The switcher sent a 1/10th...
of a second image (about 2 frames) to the Super VHS video recorder from each camera each second (the remaining time was lost in the switching process). The image was sufficiently long to capture the information needed and only a few cases were lost because the subject vehicle moved out of range during switching. Generally 2 to 3 seconds of video tape information were recorded for each vehicle passing the intersection.

Television monitors were used to align the viewing angle of the cameras and to ensure that the cameras were providing good quality images. Automatic apertures were not used because they were influenced by the brightness of the reflected light from the vehicles. As lighting conditions changed throughout the day the cameras had to be adjusted manually to ensure good lighting inside the vehicle, which generally meant slightly overexposing the vehicle image.

Electricity for the cameras and video recorder was obtained from a portable generator and a nearby building. The cameras were shielded from rain and the other equipment was operated from within a van.

3.2.2.2 Direct Observers

Four research assistants (2 male and 2 female) served as observers and rotated through the two observation points located near cameras 1 and 2 which provided views of the driver and passenger sides of the vehicle. Observers were shown the viewing angle of the cameras so they would not block the cameras, but were otherwise free to move around to obtain the best visual angle. They recorded, on a checklist, the type of improper seat belt use observed, the approximate age and sex of the driver, and the time at which the observation was taken. Which vehicle to observe was determined by a coordinator who ensured that all target vehicles were observed as well as a sample of non-target vehicles. The time of the observation (accurate to 1 second) was recorded to allow matching the direct observations with those on the video tapes which had the time superimposed on them.

For most of the observations the direct observers did not communicate and independently recorded their observations. However, for approximately 50 observations they communicated using portable radios. This allowed them to take advantage of the information that could be obtained from their different viewing angles. Training for the observers was limited, and consisted mainly of viewing 15 target vehicles with feedback as to what the improper use was.

3.2.2.3 Indirect Observers

Indirect observers (2 males and 2 females) viewed the video tapes in the laboratory. When viewing the target vehicles it was necessary to search the video tapes to locate the observations by means of a sequence number taped on the vehicle and visible on the video tape. When looking at an observation the observers stepped through the video tape one frame at a time, and were able to review each segment as often as necessary to reach a decision. Training for these observers was limited, but all of the observers had participated in the collection of the direct observations and were familiar with the improper use configurations being used.

For the non-target vehicles the timing information recorded on the video tape was used to locate observations by the two observers (1 male and 1 female) who had
not worked on previous parts of the study. A two day training program was provided. The observers viewed the tapes independently, and then compared their results. Where there were disagreements, a third observer worked with the other two to arrive at a consensus. The consensus result was used as the most likely 'correct' response in analyzing the data.

3.2.3 Target Vehicles

Four vehicles (Honda Accord, Ford Tempo, Nissan Micra, Oldsmobile Omega) were used for the target observations and four research assistants drove the vehicles (alternating the role of observer and driver). At a staging area (shopping centre parking lot), approximately 1 km before the observation point, a research assistant adjusted the seat belt of the target vehicles to introduce a wearing problem following an established order of trials. An identification number was written on the vehicle windshield, and the vehicle was driven, in the normal traffic stream, past the observation point. Once past the observation point, the driver stopped the vehicle, adjusted the seat belt properly and returned to the staging area. Only two vehicles were introduced to the traffic stream at any one time.

3.3. Results

3.3.1 Accuracy of Target Vehicle Observations

Results of the data analyses for both direct and indirect observations are presented in Table 3. Direct observers on the driver's side were able to correctly identify nonuse of a seat belt 78% of the time, but this was lower (58%) when the observer was on the passenger side of the vehicle. It is interesting to note that the indirect observers, working from the video tapes, had more difficulty identifying that a seat belt was not worn. Correct use was also more accurately identified by direct observers than indirect observers. Identifying a high lap belt was almost impossible for observations taken from the driver's side of the vehicle and the accuracy from the passenger side was only 50%. The accuracy of identifying the three levels of slack (minimal, 25mm; moderate, 75mm; excessive, 125mm) was low (less than 40%), but when the levels of slack were collapsed accuracy improved to close to 70%.

The indirect observations seem to be slightly more accurate than the direct observations, and when two indirect observers worked in pairs, comparing their results as they worked, they produced the most accurate observations.

Estimates of accuracy varied by the type of vehicle and between observers. Overall accuracies, from the drivers side, varied from 42% to 62% across the four vehicles used in the study for direct observations and from 50% to 68% for indirect observations. The best trained observer (considerable experience with seat belt research) was able to achieve accuracies over 80% on most variables from the video tape data. The best overall accuracy amongst the direct observers was 63%, obtained by the most experienced observer. The data on observer accuracy indicates the need and importance of a good training program for observers.
3.3.2 Inter-observer Reliability of Non-Target Observations

The data indicating the consistency of responses from the 1000 non-target observations, extracted from the video tapes, are presented in Table 4. Overall agreement between observers on the different factors varied from 80.5% (seat belt assembly worn properly) to 99.1% (seat belt assembly worn).

<table>
<thead>
<tr>
<th>Misuse Type</th>
<th>Direct Observer Location</th>
<th>Indirect Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driver's Side</td>
<td>Passenger's Side</td>
</tr>
<tr>
<td>Not Wearing</td>
<td>77.8</td>
<td>58.3</td>
</tr>
<tr>
<td>n 36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Correct</td>
<td>65.5</td>
<td>65.5</td>
</tr>
<tr>
<td>n 58</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Behind Back</td>
<td>73.0</td>
<td>59.5</td>
</tr>
<tr>
<td>n 37</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Under Arm</td>
<td>54.8</td>
<td>41.9</td>
</tr>
<tr>
<td>n 31</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>High Lap</td>
<td>6.9</td>
<td>50.0</td>
</tr>
<tr>
<td>n 34</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>Minimal Slack (25mm)</td>
<td>31.3</td>
<td>18.8</td>
</tr>
<tr>
<td>n 32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Moderate Slack (75mm)</td>
<td>37.9</td>
<td>31.0</td>
</tr>
<tr>
<td>n 29</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Excessive Slack (125mm)</td>
<td>30.0</td>
<td>35.0</td>
</tr>
<tr>
<td>n 20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Some slack</td>
<td>67.9</td>
<td>53.1</td>
</tr>
<tr>
<td>(collapsed across levels of slack)</td>
<td>81</td>
<td>81</td>
</tr>
</tbody>
</table>

<sup>1</sup>Four indirect observers worked independently on coding the data.

<sup>2</sup>The four observers were paired, and the pairs worked together coding the data and reaching a consensus decision when there was disagreement.

Note: Table adapted from Biokinetics, 1991b.

In addition to calculating agreement in terms of all responses, agreement was also calculated based on the number of positive responses provided by either observer which provides an estimate of the maximum incidence of each variable. The overall agreement rate is influenced by the frequency of occurrence of a misuse type. A misuse type that occurs infrequently could have a very high accuracy rate because of the large number of negative responses. Agreements based on the
incidence rate ranged from 29% (high lap belt) to 99.1% (seat belt assembly worn).

Table 4: Agreement and Incidence Data from 1000 Indirect Observations

<table>
<thead>
<tr>
<th>Misuse Type</th>
<th>Data from observer 1 and 2 only</th>
<th>Consensus data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample</td>
<td>Num. of Positive Responses</td>
</tr>
<tr>
<td>Seat belt assembly worn</td>
<td>1000</td>
<td>854</td>
</tr>
<tr>
<td>Seat belt assembly worn</td>
<td>713</td>
<td>270</td>
</tr>
<tr>
<td>Shoulder belt:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>worn properly</td>
<td>854</td>
<td>369</td>
</tr>
<tr>
<td>behind back or seat</td>
<td>854</td>
<td>1</td>
</tr>
<tr>
<td>under arm</td>
<td>854</td>
<td>22</td>
</tr>
<tr>
<td>on neck</td>
<td>854</td>
<td>92</td>
</tr>
<tr>
<td>off shoulder</td>
<td>854</td>
<td>9</td>
</tr>
<tr>
<td>moderate slack</td>
<td>854</td>
<td>25</td>
</tr>
<tr>
<td>excessive slack</td>
<td>854</td>
<td>120</td>
</tr>
<tr>
<td>twisted</td>
<td>854</td>
<td>32</td>
</tr>
<tr>
<td>held</td>
<td>854</td>
<td>10</td>
</tr>
<tr>
<td>Lap belt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>visible</td>
<td>854</td>
<td>713</td>
</tr>
<tr>
<td>worn properly</td>
<td>713</td>
<td>583</td>
</tr>
<tr>
<td>high</td>
<td>713</td>
<td>28</td>
</tr>
<tr>
<td>twist</td>
<td>713</td>
<td>14</td>
</tr>
</tbody>
</table>

Note: Table adapted from Pedder, 1991.

3.3.3 Incidence of Misuse

The incidence of misuse was determined by taking all cases in which the two observers (indirect, non-target cases) disagreed and having a third, experienced observer, review the video tape with them to arrive at a consensus decision. The incidence data are presented in Table 4.

The data indicate that 86% of the observed drivers were wearing seat belts which is consistent with other surveys conducted in the area. Of the cases in which the seat belt was being used, and in which the shoulder and lap belts could be seen, only 46.7% were considered to be wearing them properly. The largest misuse
types were excessive slack (20%), shoulder belt rubbing on the neck (18%), and high lap belt (11%). Shoulder belt slack (excessive and moderate) was identified in 24% of the cases. Twisted shoulder belts were observed in 6.6% of the cases and twisted lap belts were observed in 3.1%.

3.4. Discussion

The results indicate that reasonably accurate data on the improper use of seat belts can be obtained, but that accuracy can be improved with better training. Interobserver agreement, for non-target vehicles, was relatively high (with well trained observers), but this must be considered in light of the accuracy data which were presented. Nonetheless, the incidence data are accurate enough for estimating the level of improper seat belt use in the population.

The level of improper use of seat belts is surprisingly high, although it is consistent with the data presented by Torrington and Hall (1981). The misuse rate is much higher than that found by Booth (1988) and Bowman and Rounds (1989). Booth's results were based on a sample with a similar seat belt wearing rate (90%) and in which most of the vehicles were equipped with automatically adjusting seat belts as was the case in this study (almost all vehicles in Canada are equipped with automatically adjusting seat belts), but he reports less than 4% misuse rates, mostly due to manually adjusted seat belts. The discrepancy may be due to the nature of the current study which was to specifically look at misuse whereas the other studies were attempting to estimate belt use rates, with improper use as a secondary factor.

The accuracy data indicate that training is very important in obtaining accurate misuse data. The more experienced observers achieved much better accuracy. For the analysis of the non-target vehicles a training program was developed and is probably responsible for the high level of inter-observer agreement. The accuracy data from both the direct and indirect observers suggest that better results can be obtained if the observers can communicate with each other to reach a consensus on what the misuse is. The direct observation data presented were collected without the observers being able to communicate, but a small sample of data with communication between observers was collected and these data indicated an increase in the accuracy of the results.

4. GENERAL DISCUSSION

Previous research has suggested that the improper use of seat belts could result in a reduction in their effectiveness. The frequency of improper use was not well quantified in the literature, but it there was a suggestion that it might be high. The results of the current study indicate that in fact misuse of seat belts is relatively high. The data also indicate that measuring improper seat belt use is possible with both direct (roadside), and indirect (video tape recordings) observation techniques.

Recording the observation data on video tape for later analysis was selected as one of the better methods for collecting the data. The data extraction and analyses conducted for this study has confirmed the usefulness of this methodology. Having the video tapes to review the data and to confirm unusual findings has been very useful. Whether such a system is needed for a larger scale study is not
clear, but it is likely that it would add to the data integrity. There were additional costs associated with recording the data because staff had to be available to set the system up and to monitor it during recording. After the data were collected the video tapes had to be reviewed to extract the observations. The staff time for this system was almost twice that required for direct observations.

The direct observation data indicated that reasonably accurate estimates of improper seat belt use can be obtained at the roadside. An intensive training program would assist the observers in collecting the seat belt use data more accurately. The cost of direct observation is lower than for other systems, but observers must work under constraints as they try to get the observation data in the short time a vehicle is stopped and this may contribute to lower accuracy.

It would appear that both methodologies are effective ways of measuring the improper use of seat belts. From a researcher's point of view, using video tape to record the information and then to extract it later is the preferred method. The ability to recheck the data, and to return to it for additional information are very important benefits. From an operational point of view, the direct observation method would be the best. The data can be collected quickly, site selection is not restricted by the need to install equipment, and costs may be somewhat lower.

One question not addressed in the study, but of concern given the level of improper use, is the relative contributions of poor seat belt design and lack of knowledge of proper seat belt use to the problem. Future research will need to determine if educational programs can correct some of the problems identified in this research, or if vehicle manufacturers need to consider potential improper use of seat belts when they design these systems.

5. REFERENCES


Mandatory Hazard Perception Testing as a Means of Reducing Casualty Crashes Amongst Novice Drivers

Michael Hull
Principal Research Officer
VIC ROADS
Australia
Mandatory Hazard Perception Testing
as a means of Reducing Casualty Crashes
amongst Novice Drivers

ABSTRACT

The crash rate amongst novice drivers in the State of Victoria, Australia varies (depending on age) between three and five times higher than the rate for more experienced drivers.

A road safety conscious community expects a decrease in this road toll and is prepared to support measures directed to that end.

A commonly held belief is that additional in-car training can increase road safety awareness in young drivers. Research in Australia and internationally does not support this contention.

There is considerable evidence to suggest that novice drivers rapidly acquire the motor skills required to successfully control a car.

The evidence would suggest that novice drivers take a great deal longer to acquire the cognitive skills dealing with how they look for hazards, how they interpret what they see, and what they do about it.

There is some evidence to suggest that individuals can be tested for these cognitive skills. There is also some evidence to suggest that where deficits are discovered, individuals can be trained to compensate for the deficits.

The State of Victoria has now enacted legislation which imposes restrictions on the type of vehicle that may be driven until a Hazard Perception test is passed. It is planned to further extend the legislation so that a probationary driver licence holder may not become a full driver licence holder simply by the passage of time but will require successful completion of a Hazard Perception Test.

A pilot Hazard Perception Test has been developed and is currently undergoing early trials. A mandatory mass testing process is required to be in place by August 1992 for all Probationary drivers wishing and eligible to progress to a full driver licence.

The paper details the rationale underlying the Hazard Perception Test and potential strategies for its future applications.
MANADATORY HAZARD PERCEPTION TESTING
AS A MEANS OF REDUCING CASUALTY CRASHES
AMONGST NOVICE DRIVERS

Michael Hull
Principal Research Officer
VIC ROADS, Melbourne Australia

1. INTRODUCTION

1.1 THE NEED FOR FURTHER TESTING

Novice drivers, in Victoria as in many comparable jurisdictions, have a higher rate of involvement in crashes causing injury or death. Their rate is three to five times higher (depending on age) than for more experienced drivers. Figure 1 demonstrates this point.

FIGURE 1
VICTORIA
CASUALTY CRASH RATES

ALL CRASHES IN VICTORIA 1984 - 1989
CARS & CAR-DERIVATIVES BY AGE GROUP

Absolue No. of Crashes (Thousands)

Despite the decrease in absolute numbers of crashes over time the percentage of crashes in which novice drivers are involved remains high relative to their

1 Derived from VIC ROADS Mass Crash Data.
proportion of the population and there is substantial community support for measures to reduce their risk.

This community support is relatively extraordinary as it clearly does not translate, as it has in other countries, into community support for general measures which restrict the freedom of young people, for example curfews.

Given that the vast majority of first-time car licence applicants in Victoria are aged between 18 and 21, the social and economic costs of injury and death of novice drivers is extremely high. The State has invested substantial sums in education, health care, family allowance and other services and has hardly begun to derive a benefit by way of direct and indirect tax.

The youth of those drivers who are permanently disabled places an additional burden on the tax-payer which may be a burden that lasts for the next 60 years in terms of ongoing health care, social security payments and lost productivity.

Of equal importance is the strong public perception that the crash rate of novice drivers should be significantly reduced.

1.2 OPTIONS FOR FURTHER TESTING

1.2.1 Option 1: In-car Training and Testing

Community feeling tends to support the belief that more training produces safer drivers.

The international research literature does not provide strong support for this view.\(^2\)

The attempts made by a number of researchers over the past 30 years to break down the driving task into a number of sub-tasks has provided an impractical number of sub-tasks for training and assessment, given the staffing resources of driver licensing authorities or the Private Sector.

Moreover the capability of novice drivers to perform the necessary motor tasks associated with car driving is rarely challenged. It is a fact of human life that individuals behave differently when observed or supervised. Novice driver behaviour whilst under instruction is not necessarily representative of their behaviour when in sole control, un-supervised.

In summary it seems that, pending significant improvement in the extent to which in-car training produces a reduction in the crash risk, further training in-car is not warranted. A recent Norwegian study,\(^3\) whilst generally replicating

\(^2\) Lund (1986); Hurst (1985)

\(^3\) Glad (1984)
the findings cited above, also reported an increase in crash involvement, further indicating the need for caution in adoption of this approach.

The evidence is strong that, whilst motor control is not a major problem for the novice driver, elements of driving-related aggression\(^4\), inappropriate confidence in one's own driving ability\(^5\) and higher risk-taking behaviour and inadequate hazard perception\(^6\) are major factors. Under these circumstances it is probable that in-car training will not produce a reduction in the crash rate. Further, by stressing the motor control aspects of the driving task, it may well encourage driving behaviours that will lead to increase in the crash rate. At the very least it gives an inappropriate message to novice drivers that motor control skills are the most important component to safe driving.

The bottom line in a period of economic contraction must certainly be that in-car driver training does not produce an acceptable road safety benefit to cost ratio.

1.2.2 Option 2: More Demanding Knowledge Tests

In the most developed countries, driver licence tests generally expect of licence applicants a standard of knowledge of local road law, of car handling skills and perhaps also road-craft. Such tests vary considerably in the way they are constructed.

In Victoria, driver licence knowledge tests have been designed according to psychometric principles. Given unlimited human and physical resources it would be possible to produce more efficient tests. However, as mass testing tools, the Victorian driver licence knowledge tests compare favourably with aptitude tests and other psychological tests designed for mass screening applications.

Victorian driver licence knowledge tests are derived from handbooks published by VIC ROADS which summarise road law and road craft in a form which has an established reading level of 12 years of age. The tests are composed of multiple choice questions, with three optional answers one of which is the correct response. The pass mark on all knowledge tests is set at 80%.

Handbooks and knowledge tests are regularly updated in respect of changes in road law and recommendations in respect of road craft.

Most Victorians live in Melbourne and, in that rapidly expanding city have a genuine need for private transport to go about their daily lives. In non-metropolitan areas, the need for a car is, of course, even greater. Government

\(^4\) Lewis (1981)
\(^5\) Matthews (1986)
\(^6\) Bragg (1986)
is committed to mobility for all citizens including the handicapped.

It is in the interests of the community that those who drive do so with a driver licence. The driver licence is at least a guarantee of having met a minimum standard on knowledge of road law and road craft and the capacity to control a car on a public road. Potentially forcing significant segments of the population into unlicensed driving by raising the difficulty of tests so as to fail many applicants is to abandon the concept of a minimum standard for driving by default.

Unlicensed drivers who are involved in a casualty crash may not be eligible for financial assistance from the Transport Accident Commission to pay hospitalisation and medical expenses associated with road crashes. Thus any change which encourages unlicensed driving runs the risk of inflicting severe financial hardship not only on the unlicensed driver but on all those injured in a crash in which he or she is involved.

Eventually, more than 90 of each 100 car driver licence applicants achieve the minimum standard to acquire a licence. Given the demographics and economy of Victoria, this level is required.

Under the circumstances, such gross measures as increasing the pass mark on knowledge tests, or increasing the level of difficulty of the knowledge tests, or on-road driving tests will be counter-productive in road safety terms.

1.2.3 Summary of Options

The existing testing procedures, whilst being constantly refined, are not likely to produce the extent of change in crash rates that is expected by the community.

It has not been possible, in Australia or overseas, to demonstrate that a better score on a knowledge test leads to a decreased crash rate.

Existing tests are therefore not predictive of either crash involvement or good driving behaviour.

The existing tests are best seen as filling a gate-keeping role. They prescribe a minimum standard of theoretical knowledge and motor skills which can reasonably be required before a person is permitted to drive legally.

2. A NEW TEST

2.1 GENERAL PRINCIPLES

There is a need to improve skills associated with the broad driving task across the population.
At the same time, it is not desirable nor politically possible to prohibit a significant percentage of the population from driving legally, by refusing them a licence.

There is particular concern about the crash involvement of novice drivers. They are currently 3 to 5 times more involved than older drivers. There is concern about the fate of passengers of novice drivers. There is also concern about other road users being innocently involved in crashes caused by novice drivers.

The way in which we approach the task of reducing the crash rate of novice drivers should not affect the ability of novice drivers to drive a car, particularly since driving is often directly or indirectly required to earn a living.

On these grounds a new form of testing is required which will be described later. Rather than assessing motor skills and "intellectual" knowledge of road law and road craft, the new test aims to assess those elements of cognitive functioning which affect the driving task. This test is known as the Hazard Perception Test.

The application of Hazard Perception to mass driver licence testing is, so far as we are aware, new. We are aware of work done along similar lines in other jurisdictions but such risk has tended to be in depth with special sub-groups, such as cardio-vascular accident patients.

The new cognitive test is scheduled to start on 1 August, 1992. In its first year of operation, it is anticipated that over 100,000 novice drivers will be assessed.

3. THE HAZARD PERCEPTION TEST

3.1 DEFINITIONS

3.1.1 Hazard

A hazard can be defined for our purposes as a condition or event, the existence of which presents the risk of harm occurring to some person or property unless appropriate timely action is taken by the driver.

3.1.2 Perception

Perception, for our purposes, and probably more generally, can be interpreted as the cerebral processing of visual input (more generally, auditory and tactile input require perceptual processing too). It is important to note that perception is not appropriately defined in terms of visual skills (where to look) nor in terms of visual technique (how to look). These visual components are necessary for input to the perceptual process but they are not, of themselves, sufficient.

By implication it is assumed that the visual processes are substantially normal. This includes an assumption that the eyeball, the optic, ophthalmic and
oculomotor nerves and the visual cortex are not noticeably damaged by trauma or pathology. It is proposed that these are matters that are appropriately dealt with by ophthalmologists or optometrists and ought to be detected prior to licensing, either by previous medical examination or by the visual test first conducted when a Learner Permit is issued.

Perception, in this definition, is a "black box", the operation of which is incompletely understood. Fortunately a number of the outputs of perception are known and are subject to quantification. These outputs necessarily form the basis of a Hazard Perception Test.

3.2 HAZARD PERCEPTION

Driving is a complex psycho-motor behaviour that demands continual interaction with the environment in which the vehicle is operating as well as interaction with vehicle controls. Research indicates deficits of novice drivers in perceptual, cognitive and associated vehicle control skills. A number of these deficits are listed below.

3.2.1 Poor Detection and Assessment of Hazards

Novice drivers have difficulty in perceiving hazards. Brown (1982) reported that less experienced drivers were relatively poor at identifying a variety of distant hazards, although they operated at a similar level in detecting closer hazards. This is consistent with eye movement studies which have demonstrated that novice drivers do not scan as far horizontally and into the distance as more experienced drivers. The same study showed that novice drivers made less use of their mirrors and concluded that the search and scan patterns of novice drivers impaired their ability to detect circumstances with high crash potential.

There is also evidence that novice drivers' failure to recognise hazards often results from their excessive concentration on non-moving objects.

3.2.2 Field Dependence

Field dependent people are those who have difficulty in extracting salient information from a complex background, for example, detecting a figure embedded in a camouflaged background. According to Barrett and Thornton (1968), there is evidence that field dependence increases with age up to about 21 years of age. Further studies, including Harano (1970) have correlated field dependence with crash involvement.

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7 Macdonald (1987); Hull (1990); Soliday (1972); Barrett (1968); Harano (1970); Mourant (1972).

8 Mourant (1972).

9 Soliday (1972)
3.2.3 Evasive Action

Clayton (1972) found that young drivers were over-involved in panic reactions. There was evidence that they could not process all available perceptual information well enough so, instead of responding correctly, they simply tried to stop as quickly as possible, and, in so doing, they lost control.

3.2.4 Selective Attention

Novice drivers have been found to be inferior to experienced drivers in matching a driving scene presented directly ahead with one in a rear view mirror. The effect is a misinterpretation of information presented in the mirror.

MacDonald (1987) found that novice drivers were more likely to miss seeing hazards, and tend to take longer to notice them. They pay more attention to non-moving hazards, often at the expense of more important moving hazards associated with the changing traffic situation. They are less able to put together all the various input (from vision, hearing, etc.) into an overall assessment of danger. They assess the level of risk within a narrower range because they are less able to discriminate the finer differences. She proposes that they process information less actively, display fewer changes in where they look, have less ability to switch attention from one thing to another and use less of the information that is available for reaching a decision about what to do.

3.2.5 Greater Risk-taking

There are other factors relating to novice drivers that are also of concern. Novice drivers are more inclined to take risks. This results in driving at higher speeds, driving whilst intoxicated, accepting narrow gaps and accepting shorter headways.

Whilst there is evidence that novice drivers actively choose to drive at higher risk, there is also support for the belief that novice drivers are unaware of the risks of certain driving behaviours. For example Bragg (1982) found that inexperienced drivers considered speed to be less risky than experienced drivers.

4. DEVELOPING THE TEST

4.1 GENERAL REQUIREMENTS FOR THE HAZARD PERCEPTION TEST

The Hazard Perception Test is proposed as a mass screening test for all Victorian drivers wishing to proceed from a Probationary to a Full driver licence. Thus the Hazard Perception Test would be taken most often by novice drivers between the ages of 20 and 21 after two to three years of unsupervised driving. Under circumstances where the test is to be applied to 100,000 Victorians a year in situations where conditions are not as controlled as they
would be in a laboratory, face validity is an important consideration to maintain credibility of the test in the eyes of the community and to ensure rigorous attention to detail by VIC ROADS and possibly other staff who will administer the test.

Thus any mass test of novice driver hazard perception abilities necessitates the inclusion of appropriate and relevant types of traffic situations.

It is also appropriate to include driving manoeuvres which could be classified as *unsafe driver actions* for the population as a whole. These actions are often precede crashes.¹⁰

4.2 PSYCHOMETRIC REQUIREMENTS

4.2.1 Validity

Any test must, at the very least, demonstrate good face validity. The test must also discriminate on the basis of crash involvement. Given that the test focuses on interactions between the driver and the environment, stimuli need to be dynamic and have a high degree of realism.

Ideally, it should be possible to demonstrate essential validity by determining a predictive relationship between the score on the Test and appropriate measures of driver experience and driver safety. Such a demonstration requires a substantial prospective study. This will not be possible in the short period allowed between development of the test and its introduction as a requirement for "graduation" to a full licence in Victoria.

An imperfect alternative assessment of validity is a retrospective study in which a relationship can be demonstrated to exist between score on the Test and driver experience on the one hand and the number of casualty crashes on the other. A preliminary study of such a type has been completed using approximately 100 recruits at the Victoria Police Academy, ranging in age from 18 to 35 years. The results of this preliminary study are reported in this paper.

4.2.2 Reliability

In addition to validity, the test must be replicable. That is to say, it should detect similar deficits in the same person when that person is retested. To date, replicability has been only partly tested. Police recruits were exposed to two, roughly parallel, versions of the test and the results are presented in this paper. It is planned to test the same recruits at the end of their 12 week training period.

¹⁰ Charlesworth (1976)
4.3 TEST CONTENT

4.3.1 Derivation

The theoretical content of the test derives from the brief summary of research provided above and given in more detail in a previous paper.\textsuperscript{11} Nonetheless, given the proposed application of the test to in excess of 100,000 members of the public each year, there remains a need for demonstrable relevance to the driving task in order to ensure public acceptance of the test mechanism.

In common with most other driver licensing jurisdictions, Victoria maintains a mass crash database containing records of all crashes involving injury or death. A facsimile of the crash report form is incorporated as Appendix 2. The crash report form is completed by Victoria Police Members attending the crash scene and is later further analysed by VIC ROADS. The database material contains a complex analysis of road user movements, including relative direction of travel of all parties to the crash which is known as Definitions Classifying Accidents (DCA). DCAs for 1987 and 1988 were analysed by the author and the results of that analysis are contained in the figure following.

\textbf{FIGURE 2}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure2.png}
\caption{DCA Column Groups 1986-1988
\% Drivers 20 yrs or less involved}
\end{figure}

\begin{itemize}
  \item Hull (1990)
\end{itemize}
Given that drivers aged 18 to 20 years represent about 12% of the driving population, there was substantial over-representation in a number of crash categories. However, those crashes occurring at intersections, those involving rear-end crashes and those in which a vehicle (often without another vehicle involved) ran off the road were more substantially over-represented and were therefore selected for treatment.

This approach finds some support in a recent publication by the Australian Road Research Board\textsuperscript{12}. The authors of this report sought to develop a more in-depth approach to analysis of data from the Mass Crash database for crashes at urban intersections of arterial and local roads. Their findings are summarised in the table below:

\begin{table}
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
Accident Type & Driver 1 & Driver 2 & Pedestrians & Cyclists \\
\hline
Cross Traffic & 87 & 87 & & \\
Right Near & 92 & 92 & & \\
Right Against & 90 & 90 & & \\
Rear End & 85 & 85 & & \\
Single Vehicle & 91 & & & \\
Pedestrian & 67 & & 67 & \\
Pedal Cycle & 26 & & & 26 \\
\hline
\end{tabular}
\caption{Numbers of Different Types of Roads Users Involved in each of the Accident Categories Studied\textsuperscript{13}}
\end{table}

Whilst this study did not break down its analysis into age groups, it is significant that the first five categories in the table match the categories determined by the present author's research. It should be noted that the first three categories of the table deal with crashes at intersections, whilst the fourth and fifth entries respectively deal with rear end crashes and single vehicle crashes.

Further research in progress at the Australian Road Research Board provides some additional confirmation of the findings underpinning the content of the Hazard Perception Test\textsuperscript{14}. Based on 1988 VIC ROADS Mass Crash data a further analysis of Definitions Classifying Accidents is in progress which

\textsuperscript{12} Cairney & Catchpole (1991)

\textsuperscript{13} Adapted from Cairney & Catchpole (1991), page 6.

\textsuperscript{14} Personal Communication, John Catchpole, Experimental Scientist, Australian Road Research Board.
provides an age breakdown of the data and provides a percentage of crashes for each DCA group measured against a baseline of drivers aged 30 to 59 years.

This data also demonstrates elevated rates for novice and younger drivers in the single vehicle, rear end and intersection categories. These findings are illustrated in the table following. It should be noted that an asterisk (*) appearing in columns 3 and 4 alongside the percentage in that column indicates an over-representation of younger drivers. The asterisked items correspond well with the findings of the present author.

**TABLE 2**
**ANALYSIS OF 1988 MASS CRASH DATA INDICATING PERCENTAGE REPRESENTATION OF YOUNGER DRIVERS RELATIVE TO 30-59 YEAR OLD DRIVERS**

<table>
<thead>
<tr>
<th>Accident Description</th>
<th>DCA</th>
<th>% age Drivers involved compared with drivers aged 30-59</th>
<th>TOTAL young drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian Crashes</td>
<td>100-109</td>
<td>38.8</td>
<td>637</td>
</tr>
<tr>
<td>Adjacent Directions</td>
<td>110-119</td>
<td>31.2</td>
<td>1908</td>
</tr>
<tr>
<td>Opposing Directions</td>
<td>120-129</td>
<td>40.0</td>
<td>1638</td>
</tr>
<tr>
<td>Same Direction</td>
<td>130-139</td>
<td>33.0</td>
<td>2427</td>
</tr>
<tr>
<td>Off Path on Straight</td>
<td>170-179</td>
<td>82.5*</td>
<td>1111</td>
</tr>
<tr>
<td>Off Path on Curve</td>
<td>180-189</td>
<td>85.5*</td>
<td>583</td>
</tr>
<tr>
<td>Rear end (rear vehicle)</td>
<td>130-132</td>
<td>49.9*</td>
<td>1085</td>
</tr>
<tr>
<td>Rear end (front vehicle)</td>
<td>130-132</td>
<td>22.0</td>
<td>954</td>
</tr>
<tr>
<td>U-turn (turning vehicle)</td>
<td>140</td>
<td>37.7</td>
<td>122</td>
</tr>
<tr>
<td>U-turn (straight ahead)</td>
<td>140</td>
<td>45.7*</td>
<td>131</td>
</tr>
<tr>
<td>Struck Parked vehicle</td>
<td>160</td>
<td>60.8*</td>
<td>122</td>
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</tbody>
</table>
Since the representation of novice drivers 18 to 20 years in the driving population is of the order of 12%, a figure greater than 12 in the third column of the table above would indicate a degree of over-representation by this group. An examination of the Table will indicate substantial over-representation in most categories. However the categories Off Path on Straight, Off Path on Curve, Struck Parked Vehicle, U-Turn (travelling straight ahead), Rear end collision (rear vehicle) and intersection crashes (Adjacent Directions, Opposing Directions, Same Direction) show very high levels of over-involvement.

In summary, the areas in which the over-representation of novice drivers is extraordinarily high are rear-end crashes where the novice is driving the following car, crashes involving striking a pedestrian, crashes where there is conflicting traffic (such as at intersections) and crashes involving a single vehicle. It is clear that intervention in these areas has the potential to substantially reduce novice driver crashes.

To justify an intervention using a hazard perception approach in this area it is necessary at least to demonstrate a rational relationship between perception and these categories of crashes.

Rear end crashes (where the novice is in the following car) can be explained in terms of hazard perception. It is well established that novice drivers allow less following distance than more experienced drivers. Two components of human behaviour affect following distance. These are self-assessed reaction time and self-assessed time to process visual input.

Since novice drivers have more rear end crashes than more experienced drivers, their assessment of their own reaction time and/or their assessment of their perceptual processing time is inaccurate. Of the two elements, it is more likely that there is an inaccuracy of the self-assessment of perceptual processing time since it is more difficult to evaluate and the means of evaluating it are less direct.

Striking a parked vehicle is a classic case of either no perception or inadequate perception. More complex situations in which a parked vehicle is struck are those that involve other moving vehicles. A simple example is where a novice driver strikes a parked vehicle, whilst allowing excessive separation between his own car and a car coming from the opposite direction. Misperception is a possible inference in such cases.

Crashes involving U-turns and those involving right turning vehicles15 appear, at first sight, unusual in that many involve the novice driver travelling straight through (that is, not turning). Such behaviour can be rationalised in terms of the turning vehicle not being seen by the novice driver or by the novice driver assigning inadequate perceptual processing to vehicles over which he/she legally has right of way.

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15 Cars are driven on the left in Australia. A right turn therefore resembles a left turn in countries where cars are driven on the right.
The novice driver going straight ahead may fail to see the U-turning car or assume that it will give way.

Another common crash at intersections involves a novice driver colliding with the rear of the vehicle ahead slowing to perform a left turn. Either the novice does not see the left indicator of the leading vehicle or fails to allocate sufficient mental processing to the implication of the signal. Given the relative inexperience of the novice and the complexity of potential traffic movements at intersections such an oversight can be understood, though not accepted.

In Victoria at present, right turning vehicles have priority over left turning vehicles. Particularly in the case of the intersection of two-way four-lane roads a left turning vehicle may have difficulty in seeing a right turning vehicle before it actually enters the intersection.

Right turning vehicles have priority over left turning vehicles. The view of a left turning novice may be obstructed by other traffic at the intersection.
In such cases it may be impossible to see the turning vehicle until a dangerous situation exists. The more experienced driver is aware of the hazardous potential in such a situation and probably is likely to proceed with appropriate caution.

A similar argument applies to many crashes involving pedestrians. Particularly in the case where a pedestrian emerges from between parked cars, it may not be possible to see the pedestrian until an emergency situation already exists. The more experienced driver can not in such a situation perceive pedestrian traffic any better than the novice. But the more experienced driver perceives environmental cues and adjusts his driving accordingly. Pedestrians for example, are more likely to be encountered in and around shopping centres and schools at starting and finishing times.

A further category of crashes in which novices are over-represented is "off path on curve". These are single vehicle crashes, more usually on high speed country roads. In these cases, no other vehicle, animal or object is involved. By definition this category of crashes involves loss of control.

It is not doubted that many of these cases involve excessive speed for the conditions. Evidence has been cited that novices do not scan the road as far ahead as experienced drivers. Under these circumstances they have less time in which to adjust speed appropriately for a curve or bend. It is also possible that novices perceive a curve or bend less effectively, not having established criteria for assessing its "tightness".

Crashes classified as "off path on straight" are more difficult to rationalise. It is probable that a substantial percentage of these crashes involve veering off the sealed surface onto gravel shoulders and it is suspected that fatigue may be a major contributor. There is evidence to suggest that novices allocate excessive perceptual processing to stationary objects in the vicinity of the road, for example railings along the sides of a bridge and it is possible that roadside furniture, perceived shortly before the driver is level with it, occasions panicky over-reactions resulting in loss of control.

4.4 Test Items

Test items have been developed on the basis of the analysis of crashes using the Definitions for Classifying Accidents along the lines suggested in the explanation of the Definitions laid out immediately above.

Test items are presented as real time moving images on computer screens and consequently it is not possible to display them on the page of a report. A brief demonstration videotape has been prepared to overcome this problem.

Test questions are captured by movie camera either from candid traffic material or from "staged" arrangements of traffic. The movie material is analysed to ensure that it complies with one (or more) of the scenarios outlined above.
Potential test material is also carefully checked to ensure that the scenario specific information in the movie clip is not readily confused with other events which can be seen in the clip.

At this stage the movie start and finish frame numbers of the clip are noted and the clip is digitised onto computer hard disk and the appropriate audio and text expositions of the question are identified and attached to the visual sequence.

Completed test items are submitted to assessment of an expert panel consisting of perceptual psychologists, Police Traffic Officers, Licence Testing Officers and teachers/test designers.

Each item is then extensively trialled prior to being considered for incorporation as a test item.

5. EVALUATION OF THE TEST

The test has recently had a preliminary trial, using 60 naive subjects of both sexes. These subjects were novice Victoria Police cadets who had not yet undergone Police driver training.

The mean age of subjects was 24.9 years. The standard deviation was 5.603. 12.4% of the sample were female.

The Australian Council for Education research initial evaluation is incorporated as an appendix to this paper. Generally, this independent evaluation indicates that the research design is 'incomplete' (i.e. not every subject answered each question). The small number of subjects made the results somewhat tentative but general indications of quality of the items could be deduced. ACER applied point biserial correlation and Infit Mean Squares to the data and determined that 1 item of the 33 in the preliminary trial failed both statistical tests whilst an additional two items required careful re-design modification before inclusion in a final test. Two additional items failed the Mean Square Infit test but not the Point Biserial Correlation test and results for a third item indicated a need for its reassessment. Two additional items failed the Point Biserial Correlation Test but not the Mean Square Infit Test whilst 3 additional items were identified as requiring further attention.

The analyst has made the point that the inconsistencies listed above between the Point Biserial Correlation test and the Mean Squares Infit test are likely due to the small size of the sample.

Figure 3 below shows a map of the jointly estimated item difficulties and subjects' scores. The vertical line in the middle of the map is the scale on which both scores and difficulties are reported. The Panel to the left of the vertical scale reports the distribution of individual scores whilst the right panel reports the estimated difficulty of each of the items. Thus item 26 was the most difficult item and items 3 and 5 the easiest items.
The distribution of subjects (left panel) is higher on the scale than the bulk of the items, indicating that the items were relatively easy for the group of subjects. This is desirable in a situation where the test is to be a minimum competency test.

The majority of items (right panel) are grouped at the lower end of the scale. It is desirable that a high percentage of questions are clustered at around the minimum competency level in order to assist in pass or fail assessments at around the minimum competency level.

The analyst makes the point that it will be necessary in the large scale pilot to ensure a larger range of abilities in subjects.

A large scale pilot is now in preparation and will derive data from upwards of 1000 subjects drawn from Public Service Administrative Officers, tertiary students, trade apprentices elderly citizens groups and, possibly, prison populations.

**FIGURE 3**

**VICTORIA POLICE ACADEMY**
**INFIT MEAN SQUARES EVALUATION OF HAZARD PERCEPTION TEST**

<table>
<thead>
<tr>
<th>Item Estimates (Thresholds)</th>
<th>07/09/91 15:04:54</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>26</td>
</tr>
<tr>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>17</td>
</tr>
<tr>
<td>1.0</td>
<td>20</td>
</tr>
<tr>
<td>0.0</td>
<td>11</td>
</tr>
<tr>
<td>-1.0</td>
<td>14</td>
</tr>
<tr>
<td>-2.0</td>
<td>29</td>
</tr>
<tr>
<td>-3.0</td>
<td></td>
</tr>
</tbody>
</table>

Each X represents 1 students
5.1 CONCLUSION

Evidence based on a small and somewhat homogeneous sample indicates a robust and reliable test with high face validity and high community acceptance based on its self-evident applicability to the driving task.

A larger scale pilot run with a much larger number of more heterogeneous subjects will be conducted during the latter half of 1991. This larger pilot is expected to provide additional data on the validity of the Hazard Perception Test.
APPENDIX 1  AN INTRODUCTION TO VICTORIA

Victoria is the smallest mainland State in Australia with area (about 100,000 square miles). It is the most densely populated Australian state with substantial areas of intensive agriculture and a relatively small proportion of grazing land. Its capital, Melbourne, has a population approaching 4 million and there are a number of provincial centres with populations between 50,000 and 100,000. Typical of all Australian states, with the exception of Queensland, the majority of Victoria's population lives in its capital.

Driver Licensing and Vehicle Registration is dealt with by a network of 36 regional VIC ROADS offices throughout Victoria. Ten of these are located in the Melbourne metropolitan area with an additional three offices on the metropolitan fringes. Major provincial cities throughout the State have VIC ROADS registration and licensing offices. Victoria Police act as VIC ROADS agents in some more remote areas.

In Victoria, driver licensing falls into four specific areas:

TABLE A-1  
DRIVER LICENSING AREAS AND TESTS REQUIRED

<table>
<thead>
<tr>
<th>LICENSING AREA</th>
<th>MINIMUM AGE</th>
<th>KNOWLEDGE TEST</th>
<th>PRACTICAL TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>MotorCycle Learner Permit</td>
<td>17.75</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Car Learner Permit</td>
<td>16.0</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Motor Cycle Probationary Licence</td>
<td>18.0</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Car Probationary Licence</td>
<td>18.0</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Heavy Vehicle Licences</td>
<td>21.0</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

In addition to these general driver licence requirements there are special Driver Certificates, with additional testing requirements, for specialist areas, such as Hazardous goods drivers, Hazardous areas drivers, Tow-truck operators, Bus drivers and Taxi drivers.

Knowledge testing is applied at all basic driver licence levels. Knowledge testing covers relevant road laws and road craft. There are approximately 250,000 Learner Permit and Probation licence knowledge tests administered annually in the State. Knowledge tests are available in 16 community languages. Handbooks are available in 12 languages.
In addition each year, about 170,000 practical driving tests are taken. These are administered by trained Licence Testing Officers. Each test takes about a half-hour. Since practical testing is done on a one-to-one level it is highly demanding of the human resources of the organisation. There are practical limitations on the nature of on-road or even off-road practical driver testing in terms of the sorts of hazards that can be realistically and safely presented. This creates a need for an alternative system which can assist in detecting driver behaviour.

**TABLE A-2**

**VICTORIA**

**ROAD SAFETY INITIATIVES IN 1990**

<table>
<thead>
<tr>
<th>ROAD SAFETY INITIATIVE</th>
<th>TIME INTRODUCED</th>
<th>GROUP AFFECTED</th>
<th>EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRADUATED LICENSING</td>
<td>August 1990</td>
<td>all novice drivers but publicised September 1989</td>
<td>3 years probation: Zero BAC vehicle power restrictions: single passenger restriction if certain offences committed</td>
</tr>
<tr>
<td>BICYCLE HELMETS</td>
<td>July 1990</td>
<td>all cyclists</td>
<td>mandatory wearing of helmets by all cyclists</td>
</tr>
<tr>
<td>IGNITION INTERLOCKS</td>
<td>October 1990</td>
<td>any serious BAC offence</td>
<td>by order of court may only drive car with device fitted</td>
</tr>
<tr>
<td>MANDATORY PROBATIONARY LICENCE FOR DRIVERS RE-LICENSED</td>
<td>October 1990</td>
<td>any driver with licence cancelled for drink-drive offences</td>
<td>implies Zero BAC for 3 years also vehicle power restriction</td>
</tr>
<tr>
<td>AUTOMATED SPEED DETECTION</td>
<td>January 1990</td>
<td>all drivers</td>
<td>substantial fines and possible automatic licence loss for speed violations recorded on camera.</td>
</tr>
<tr>
<td>ANTI-SPEED MEDIA ADVERTISING</td>
<td>January 1990</td>
<td>whole of State</td>
<td>Graphic films showing increased trauma resulting from speed in crashes</td>
</tr>
<tr>
<td>INCREASED RANDOM BREATH TESTS</td>
<td>January 1990</td>
<td>whole of State</td>
<td>More than one in three Victorian drivers will be breath tested in course of year. Substantial deterrence value</td>
</tr>
<tr>
<td>HAZARDOUS POLE TREATMENTS</td>
<td>August 1990</td>
<td>whole of state</td>
<td>An agreement has been made with utility suppliers for a major campaign against hazardous pole placement</td>
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Definitions for classifying accidents
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Eye Scanning Rules for Drivers - How Do They Compare with Actual Observed Eye Scanning Behavior?

Helmut T Zwahlen
Ohio University
Department of Industrial and Systems Engineering
USA
Paper Prepared for Presentation at the A3B02/A3B06 Sponsored Midyear Paper Session at the International Conference on Strategic Highway Research Program (SHRP) and Traffic Safety on Two Continents, Gothenburg, Sweden, Sept. 18-20, 1991.

EYE SCANNING RULES FOR DRIVERS - HOW DO THEY COMPARE WITH ACTUAL OBSERVED EYE SCANNING BEHAVIOR?

Helmut T. Zwahlen

Department of Industrial and Systems Engineering
Ohio University, Athens, Ohio 45701-2979
(614) 593-1550
ABSTRACT

The U.S. driver education and training literature was reviewed to identify rules and/or recommendations with regard to driver eye scanning behavior and strategies, where a driver ought to fixate his eyes when driving, specifically when driving through a curve. In addition, driver eye scanning behavior was recorded and analyzed for 9 drivers driving through 240 feet radius right curves (unlighted interstate entrance and exit ramps, 270 degree turns) at night with low beams. An instrumented car with a corneal reflection technique television eye scanning system was used. Each driver made a number of runs through the curves (average speed 26 mph) and the driver eye fixation sequences were analyzed for three to eight runs per driver, yielding a total of 51 analyzed runs. Of most importance for the eye fixation sequence analysis were the eye fixation positions on the curves ahead of the car. In addition to the eye fixation sequences analyzed in this study, previously analyzed spatial and temporal eye scanning data from the same subjects was used to compare the eye scanning rules with the actual observed eye scanning behavior. Matrices and histograms were established to indicate the conditional frequencies for forward and backward progressing eye fixation sequences, given a previous type of eye fixation sequence. The results showed that the expected number of consecutive forward eye fixations (including forward ending eye fixations) is 1.89, while that of backward eye fixations (including backward ending eye fixations) is 1.26. The results of this exploratory study indicate that drivers use both forward and backward eye fixation sequences and that there appears to exist no predictable simple, systematic eye fixation sequence patterns within a driver (within a run or between runs) or between drivers such as an again and again repeating sequence of one or two fixations far ahead (possibly for perception of curvature, directional control and obstacle detection) followed by one or two fixations closer in towards the car (possibly for lateral control) when driving through a curve. Since no simple and systematic sequence of eye fixations which would have been repeated again and again within a run and from run to run by a driver was discovered, it may be tentatively concluded that many different eye fixation sequences and strategies provide adequate visual input for proper curve driving. Therefore, there is probably no need for very specific, object or sequence oriented eye fixation recommendations for curve driving and for that matter for driving on a straight section of a highway.
INTRODUCTION

The U.S. driver education and training literature contains a number of recommendations with regard to driver eye scanning behavior and strategies and specifically with regard to where a driver ought to fixate his eyes when driving. One of the earliest set of perceptive driver training rules was provided by Smith and Cummings (1). They recommended to "aim high at steering, have a wide picture, keep your eyes moving, keep yourself an out and make sure they see you". The American Automobile Association (2) proposed and discussed the "brief-glance" technique for drivers to avoid a dangerous condition known as "captured attention". Aaron and Strasser (3) proposed and explained driver seeing habits which were the same as the rules published previously by Smith and Cummings (1). They recommended that drivers should develop a habit of scanning the entire traffic scene (about 300 degrees) and that their eyes should move from "left to right" in a continuous effort to assess the potential hazards. Bishop et al. (4) explained the techniques of "systematic seeing and indicated that systematic seeing involves three important steps: "center on the travel path, scan and search the traffic scene, and check mirrors and instruments (which, according to the authors can be thought of as an extension of scanning and searching)". They explained that for centering on the travel path "your reference point on a straight road should be in the middle of your path and on curved roads and turns, your reference point should be through the curve or turn, to the point where your vehicle will be positioned when you complete the turn and follow the same rules when driving at night". Some of the other recommendations given by Bishop et al. are: "scan and search the scene by looking far ahead and near and on both sides of your vehicle, look away from your visual reference point". They also proposed several ways to make the best use of vision for centering and scanning: "use central vision only on pertinent events, look at each event in the traffic scene briefly, limit the number of times you look at each event in a traffic situation, avoid looking at former events and keep all previous information in mind". Night vision and the factors affecting it were further discussed and it was recommended that drivers should scan the
darkened areas when driving at night. To lessen the likelihood of being blinded temporarily by the glare of oncoming headlights, they recommended to "look at the edge of the pavement ahead of your car until the oncoming vehicle has passed". In another publication Davis et al. (5) discussed two basic seeing rules which are to be made into a habit. They are "center on a target 12 seconds ahead, and keep your eyes scanning and searching". The authors explained that "the eyes should move from the target 12 seconds ahead to the left and to the right, they should then move to the rearview mirrors, then to the instrumented panel, and finally they should move back to the target ahead" and recommended to reduce the speed and stay in the lane. Johnson et al. (6) specifically discussed driving on two-lane highways and curves. The steps proposed by the authors when approaching a curve are: "take quick glances across the curve to identify oncoming traffic, maintain proper lane position by glancing ahead at your intended path of travel, evaluate the sharpness of the curve, slow down to a suitable speed before entering the curve, accelerate gently after entering the curve, and once around the curve, resume a safe speed". They also explained an "orderly visual search pattern" which is a process of searching critical areas in a regular sequence. Moreover, they recommended that drivers should develop the technique of "selective seeing" which is a process of selecting and identifying only those events and clues that pertain to a driving task.

Looking at the rules and recommendations found in the U.S. driver education and training literature, it appears that most of these recommendations do not make any distinction between driving through a curve or a straight section of a highway, between daytime and nighttime driving, and between driving alone as single vehicle or with other traffic present. Most of these recommendations however, make rather general statements about where to look, in the driving scene and very importantly, to move the eyes frequently to scan and search the traffic scene. Some of these recommendations stress the importance of short eye fixations, brief or quick glances and to limit the number of fixations at a specific feature in the driving scene.
There are only a few previous studies reported in the literature which have investigated driver eye scanning behavior on straight and/or curve sections of a highway. One such study by Shinar et al. (7) concluded that "drivers rely on different visual cues, for directional and lateral control, on curves than they do on straight roads". The authors stated that "instead of concentrating his fixations and presumably his attention close to the focus of expansion as he does on a straight road, on a curved road the driver concentrates intermittently on the position of the roadway ahead and the road edge (or lane markings) closer to the car". Moreover, they concluded that "drivers start scanning curves for directional cues as they approach them and resort to direct foveal fixations of the road-way close to the car for lateral placement cues". Most of the driver eye scanning behavior studies usually provide average and standard deviations for the spatial and temporal eye scanning measures, however, very few provide detailed spatial eye fixation density plots and/or eye fixation duration frequency distributions.

No studies have been found which would provide any information about the eye fixation sequences that drivers make when driving either on a straight road or through a curve. In addition, there may be problems with regard to the accuracy of the spatial and temporal eye scanning summary measures provided in some of the previous curve eye scanning studies. This is not surprising if one considers the difficulties involved in the spatial and temporal analysis of the eye fixations when driving through a curve. Since there is no fixed visual reference point (like the focus of expansion in straight driving) in curve driving, one has to work with an imaginary focus of expansion as the environmental reference point. The imaginary focus of expansion in curve driving for a given eye position in the curve is defined as a point on the horizon line where a pair of imaginary straight, extended, left and right edge lines of the driving lane meet, assuming that a driver's saggital plane coincides with the center of the visual field and is tangential to the curve radius. It is an extremely difficult task to accurately determine the correct horizontal location of the imaginary focus of expansion along the horizon on the TV screen based on a
limited field of view of the curve perspective (given by the left and right edge lines of a driver's driving lane). Depending on how accurately one determines the imaginary focus of expansion for each eye position in relationship to the perspective view of the left and right edge lines of the driving lane, the calculated mean of the horizontal eye fixation distribution can be more or less wrong. Further, depending on how accurate the perspective view of the curve as it is seen by the drivers is assumed, the results and statements with regards to the horizontal overall average of the eye fixations may not be accurate. Figure 1 shows the correct perspective views for curves with two different radii of curvature. It should be noted that because a driver’s eyes are located at a certain distance above the pavement of the flat road, the edge lines of the driving lane in the curve do not touch the horizon line as indicated incorrectly in figures published by some other authors.

If one would know with a reasonable degree of accuracy, the spatial and temporal eye scanning behavior characteristics and the eye fixation sequences of fairly experienced drivers and assuming that experienced drivers have developed adequate, sufficient and possibly near optimal eye scanning sequence patterns, one should be able to evaluate the validity of the driver eye scanning behavior rules and recommendations found in the U.S. driver education and training literature and possibly, if warranted, propose new rules. It was the purpose of this study to determine in an objective and quantitative manner, the type of Eye Fixation Sequence (E.F.S) patterns that drivers exhibit in terms of fixating successively farther away, or fixating closer in towards the car when driving through a curve and thus investigate the rules and recommendations given in the driver education and training literature.

DATA ANALYSIS

Data Base

The eye scanning behavior data used in this analysis was collected as part of a study conducted by Zwahlen (8). Driver eye scanning and performance data were collected for
Figure 1. Perspective Views of Typical Right Curves
interstate highway entrance/exit ramps (right curves, 240 feet radius, 16 feet wide, 270
degree turns, both dry and wet pavement) at night. An instrumented car (VW 412,
automatic transmission, 4 door, 4000 low beams) with an in-car TV eye scanning
recording system, a lane tracker and other electronic sensors and equipment (corneal
reflection technique television eye scanning system) was used. Nine young subjects with
an average age of 22.3 years (std. dev. 2.3) with an average driving experience of 6 years
(yearly 6000 miles) were paid to participate in the experiment. All the drivers were rather
fairly familiar with the experimental car and the TV system used for the eye scanning
behavior measurements since they usually drove from Athens to the experimental site on
route I70 and, usually before running the actual experiment, all the drivers were made to
drive in and around Athens by wearing the helmet with the TV system components. Each
driver made a number of runs through the curves (avg. speed 26 mph) and the prevailing
traffic conditions on I70 and the ramps allowed some of the runs to be performed only at
very low speeds (slow moving vehicles ahead). For this reason, eye fixation sequences for
an unequal number of runs per subject (3 to 8 runs per subject) were analyzed yielding a
total of 51 analyzed runs.

The exact sequence and spatial coordinates of all eye fixations on the road ahead, or
the adjacent flat road environment up to a radius of 290 feet were determined. Only 0.7%
of the eye fixations during curve driving were on a vehicle ahead. All forward and
backward eye fixation sequences were determined for each run and also recorded as a
function of each previous eye fixation sequence. Conditional matrices and histograms
indicating the frequency of forward or backward E.F.Ss (including forward ending and
backward ending E.F.Ss) consisting of a number of eye fixations were prepared to
quantify the eye fixation sequences. The sequences were first examined for each run, then
for all the runs for a given driver, and finally for all runs for the entire group of drivers.
This data was previously analyzed in terms of eye fixation distributions (spatial analysis)
and in terms of eye fixation durations (temporal analysis) for night driving on both tangent
and on right curve (entrance/exit ramps) interstate sections by Zwahlen (9). The two-
dimensional eye fixation distributions indicated a single mode located at \( x = 0.5^\circ \), and \( y = -0.5^\circ \) (focus of expansion at 0, 0; \( N = 11780 \)) for tangent sections and at \( x = 14.5^\circ \) and \( y = -1.7^\circ \) (imaginary focus of expansion 0,0; \( N = 8884 \)) for the right curve. The average fixation duration for the tangent section was 0.43 sec (2.3 fixations per sec) and was .29 sec (3.4 fixations per sec) for the right curve (std.dev. 0.35 sec and 0.16 sec respectively), indicating that more eye fixations are needed in curve driving which is a visually more demanding task when compared to straight road driving. Figure 2 shows the cumulative relative frequencies as a function of the fixation durations (in seconds) and it can been seen from this figure that the fixation durations for curves are considerably shorter than those for the straight sections.

DEFINITIONS OF EYE FIXATION POINT, EYE FIXATION SEQUENCE AND EYE FIXATION

An eye fixation point is defined as the point on a feature of an object or a feature of the curve environment (except the sky), where a driver has fixated his eyes for a short duration of time (about .1 to .5 sec), in such a way that visual information can be obtained with the greatest resolving power for visual detail (fovea). The coordinates of the eye fixation points for the features of the objects or for the features of the curve environment (except the sky) can be mathematically determined, provided, one knows the coordinates of the surfaces (usually assumed to be a horizontal and level plane), the horizontal and vertical angles of the eye fixation direction and the coordinates of a driver’s eye position. Figures 3, 4, and 5 illustrate the graphical definitions for the direction of single E.F.S., for forward and backward E.F.Ss and for forward ending and backward ending E.F.Ss respectively. A forward ending or a backward ending E.F.S. was obtained whenever there was no eye fixation point visible on the TV screen (eye blink or out of view) after the last eye fixation point, or when the next eye fixation point was either above the horizon or outside the 290
Figure 2. Cumulative Relative Frequencies as a Function of Fixation Durations
Figure 3. Graphical Definition for the Direction of a Single E.F.S.
Figure 4. Graphical Definitions for Forward and Backward E.F.Ss
Forward Ending (FE) Sequences

FE1  FE2  FE3  ..........  FE6  6th  4th  5th  6th

1st E.F.  2nd E.F.  3rd  2nd  3rd  2nd  1st

Car Direction in Right Curve

Backward Ending (BE) Sequences

BE1  BE2  BE3

1st E.F.  2nd E.F.  3rd

Car Direction in Right Curve

Figure 5. Graphical Definition for Forward Ending and Backward Ending E.F.Ss.

Note: For both forward ending and backward ending sequences, there was no eye fixation on the screen or within 290 feet radius after the last eye fixation.
feet curve radius region. Figure 6 illustrates and defines some typical eye fixation
sequences observed when a driver drives through a curve.

In this study, the definition of an eye fixation in the case when the driver's eye spot
moved within the same object was made dependent on two factors: the length of time of
the shorter of two adjacent "would be" fixations (separated by a saccade) and the magnitude
of the direct distance (saccade) between the two "would be" fixations in the visual plane.
Keeping a reasonable trade-off between accuracy and analysis time in mind it was decided
that in general, the longer the time of the shorter of the two "would be" fixations lasts, the
smaller the magnitude of the direct distance between these two adjacent fixations in the
visual plane had to be in order to define both as separate eye fixations. On the other hand,
the shorter the time of the shorter of the two adjacent "would be" fixations is, the longer the
magnitude of the direct distance between these fixations in the visual plane had to be in
order to define them as separate eye fixations. If the above criteria were not met in a
specific case, the shorter of the two fixations was incorporated into the larger fixation
making up one eye fixation. If a driver's eye spot moved enough (a few degrees) to
indicate that the foveal attention shifted to a different object this was defined automatically
as a new fixation regardless of the time duration and the magnitude of the saccade distance.
However, if one would define an eye fixation such that many fixations are incorporated
into one large fixation, the fixation durations increase significantly there by resulting in an
error in the summary measures of the temporal distributions.

Two computer programs were written in FORTRAN. The first one plots a top
view of each 90 degree section (total 3 sections, 270 degrees) of the right hand curve, a
point for each eye fixation, a point for each head position of the driver and a line between
each set of two points indicating a driver's eye fixation direction from the head to the
fixation point. These fixation lines are plotted only if the eye fixations were below the
horizon and within a selected maximum radius of 290 feet. Figure 7 illustrates a typical top
view plot with the eye fixation directions. The second program plots the top view for each
Subject: C.Z.

Total No. of Fixation Lines: 91

No. of Fixations Above the Horizon: 4

No. of Fixations Below the Horizon: 87

No. of Fixations on Road Surface: 62

Figure 7. Typical Top View Plot of the Eye Directions for One Run
90 degree section, each eye fixation point (below the horizon and within 290 feet radius only), and straight lines connecting the consecutive fixation points. Figure 8 illustrates a typical top view plot with the connected consecutive eye fixation points. These two typical top view eye fixation direction and consecutive fixation figures along with the definitions provided the basis upon which the conditional eye fixation sequences were determined.

**RESULTS**

The results indicated that there appears to be no discernible simple systematic eye fixation sequence pattern within and between the runs of a single driver, as well as between the runs of different drivers. Therefore, the data obtained from all the runs for all the subjects were combined for further analysis. The results further indicated that the drivers made a maximum of 7 consecutive forward eye fixations and a maximum of 4 consecutive backward eye fixations. Table 1 shows the summary matrix of forward, backward, forward ending and backward ending eye fixation sequences for all the 51 runs as a function of the eye fixation sequence that the subjects exhibited previously. It can be seen from Table 1 that a total of 643 eye fixation sequences which resulted in 1013 (forward or forward ending = 613, backward and backward ending = 400) eye fixation directions (based on 2175 eye fixation points) were analyzed.

Based upon the E.F.S results for fixations ahead of the car below the horizon and within a curve radius of 290 feet, the expected number of consecutive forward fixations (including the forward ending fixations) is 1.89, while the expected number of consecutive backward fixations (including the backward ending fixations) is 1.26. Also, the ratio between forward and forward ending sequences is 3.1 and that of backward and backward ending sequences is 6.1 indicating that the forward sequences occur more than three times as often as the forward ending sequences and the backward sequences occur six times as often than the backward ending sequences. Figures 9 and 10 further illustrate the conditional probabilities as shown in Table 1. Looking at Figure 9, it can be seen that the
Figure 8. Typical Top View Plot of the Connected Eye Fixation Points for One Run
### TABLE 1. SUMMARY MATRIX OF EYE FIXATION SEQUENCES

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Total: 643
Figure 9. Relative Frequencies of Forward E.F.Ss Given a Previous Backward E.F.S. or Backward Ending E.F.S.
Figure 10. Relative Frequencies of Backward E.F.Ss Given a Previous Forward E.F.S. or Forward Ending E.F.S.
relative frequencies of a forward or forward ending E.F.S. appear to be independent of the previous number of eye fixation points of the backward or backward ending E.F.S.. There is about 50% probability that an F1 sequence will follow a previous backward or backward ending E.F.S.. Similarly there is about 25%, 15%, 5%, 2%, and 2% probability that an F2, F3, F4, F5 and F6 sequence will follow a previous backward or backward ending E.F.S. respectively. Similarly, looking at Figure 10, it can be seen that the relative frequencies of backward or backward ending E.F.S. also appear to be independent of the previous number of eye fixation points of the forward or forward ending E.F.S.. There is about 80% probability that a B1 sequence and about 18% probability that a B2 sequence will follow a previous forward or forward ending E.F.S respectively.

**DISCUSSION OF RESULTS AND CONCLUSIONS**

The results of this study indicate that drivers use both forward and backward eye fixation sequences and that there appears to exist no predictable simple, systematic E.F.S. patterns within a driver or between drivers, such as an again and again repeating sequence of one or two fixations far ahead (possibly for perception of curvature, directional control and obstacle detection) followed by one or two fixations closer in towards the car (possibly for lateral control) when driving through a curve. Therefore, fairly experienced drivers appear to have a lot of freedom in choosing what they want to look at in the driving scene, and what combinations of E.F.Ss. they want to use to get the necessary visual driving information, without impairing their successful driving performance through a curve or for that matter most likely also on a straight section of a highway. Since no simple, systematic pattern which would have been repeated again and again within a run and from run to run by a driver was discovered and since each of these fairly experienced drivers exhibited different combinations of E.F.Ss. on each run, we may tentatively conclude that many different E.F.Ss. and strategies must provide adequate visual input for proper curve driving and there is probably no need for very specific, object or sequence oriented eye
fixation recommendations for curve driving or for driving on a straight section of a highway. Moreover, looking at the results of the spatial and temporal eye fixation analysis (9), it would appear that drivers do make considerably more eye fixations during curve driving than they do on straight road driving. One may conclude that curve driving appears to be an extremely demanding visual information acquisition and processing task when compared to driving on a straight section of a highway leaving very little spare visual capacity for the driver. Traffic engineers might also take note of this fact and limit the placement of traffic signs in curves as much as possible, especially traffic signs placed along the inside of the curve.

The observed forward and backward eye fixation sequences, the cumulative eye fixation duration frequencies, as well as the spatial eye scanning data published in (9) appear to support to some degree, some of the recommendations and rules given in the U.S. driver education and training literature. However, some of these rules cannot be supported by the results and might be inherently dangerous if one would follow them consistently and accurately, especially when driving through a curve at night. For example, "Aim high at steering" (1) is a general recommendation since it does not make any distinction between driving on a straight road or on a curve, or driving during the day or during the night. Looking at the E.F.S. results and the spatial eye fixation distributions for straight road and curve driving at night published in (9) and assuming that the eye scanning behavior of the test drivers who participated in the study is fairly well learned and fairly close to an optimal information acquisition process, one can state that drivers cannot always "aim high at steering" since they make backward E.F.Ss towards the front of the car, especially during curve driving at night. The spatial eye fixation distribution results also indicate that drivers do in fact fixate once in a while relatively close in front of the car during straight road and curve driving at night. Overall, a recommendation of "aim high at steering" qualified by adding wherever and whenever possible and feasible appears to have some validity and merit when looking at the eye scanning behavior results and would
provide a driver with a longer preview time which is desirable from a control systems and tracking point of view. According to the spatial eye fixation results and the E.F.S. analysis, in curve driving at night, the test drivers appeared not to maximize their preview time or forward fixation distance across the curve (beyond the major illumination of the lowbeams) and instead followed a strategy of placing most of their eye fixations anywhere from fairly far ahead in the curve (but still mostly within lowbeam illumination pattern) to closer in front of the car on the curve surface or on the immediate curve environment ahead.

The recommendation "Have a wide picture" (1), although somewhat non-specific, is fairly well supported by the spatial eye fixation data shown in (9), especially for curve driving at night which shows a larger horizontal dispersion of eye fixations (horizontal eye fixation average = 12.79° to the right of the imaginary focus of expansion with a std.dev. of 3.79°) when compared to straight road driving at night (horizontal eye fixation average = 0.84° to the right of the focus of expansion with a std.dev. of 1.92°) if one assumes that the horizontal width of the "wide picture" is about 10 degrees. It is assumed and fairly well established that drivers only acquire detailed visual information when fixating their eyes on an object or a road feature and not when moving their eyes from one fixation point to another. Therefore, in order to "have a wide picture" one would expect that a driver would have eye fixations over a certain area of the visual field in order to get visual details about the most important objects or road features in the driving scene. It should be noted that the most important road features and objects are below the horizon within a rectangle of about 30°H ahead and from the horizon to 6° below for both straight roads and curves which is not a large area considering the extent of a driver's whole visual field ahead.

"Keep your eyes moving", according to the authors involves glancing near and far, to the right and left, in the mirrors and at the instrument panel and looking ahead after each glance. This recommendation appears to be partially validated by the E.F.S. analysis, the cumulative eye fixation duration frequencies and the spatial results shown in (9). If one wants to move his or her eyes frequently, the eye fixation durations must be rather short.
which is supported by the temporal eye scanning behavior results (saccade durations usually much less than 0.1 seconds) especially for curve driving situations where the average fixation duration is only 0.29 seconds. Further, the spatial results indicate that the drivers do move their eyes over a certain region of the driving scene for straight road driving (most of the time within about \( \pm 3^\circ \text{H}, \pm 3^\circ \text{V} \) around the focus of expansion) and a moderately larger area (most of the time within a rectangle from about \( 6^\circ \) to \( 18^\circ \text{H} \) and about \(-4^\circ \) to \( 0^\circ \text{V} \) from the imaginary focus of expansion, centered on the outer curve lane marking stripe) for driving through a 240 feet radius right curve at night. Overall, the results indicate that drivers do in fact look ahead after making fixations close to the front of the car but not in a systematic and consistent pattern as is suggested by Smith et al. (1). "Keep yourself an out" and "Make sure you are seen" are general recommendations made by (1) and are suited more for strategic driving rules which do not recommend specific eye fixation patterns or sequences to be followed by drivers.

The "Brief-Glance" technique (2) is the one that has been claimed to avoid a dangerous condition known as "captured attention". Again, this technique doesn't distinguish between the various driving situations (curves, straight roads, day, night, traffic, etc.). However, this recommendation is similar to "keep your eyes moving" proposed in (1) and thus appears to be partially validated as a rule by the E.F.S. analysis results, the cumulative eye fixation distribution frequencies and the spatial results shown in (9). This rule does stress fixation durations which should be brief rather than long and the cumulative fixation duration frequencies for curve driving indicate that there are practically no glances with a duration of over 1.1 seconds.

Aaron et al.'s (3) statement that drivers should develop a habit of scanning the entire traffic scene (about 300 degrees) and that their eyes should move in a continuous effort to assess the potential hazards is again similar to "Keep your eyes moving", but according to the spatial eye fixation results given in (9) the horizontal extent of the recommended scanning activity (about 300 degrees) appears much too large for both
straight road and curve driving at night. Further, no reference is made with regard to any vertical scanning activity (how far ahead of the car). Again, a driver makes a continuous string of discrete eye fixations during which detailed visual information is acquired rather than picking up detailed visual information during a continuous movement of the eyes. The eyes move very quickly between two successive fixation points with no significant detailed visual information intake during these times. It should also be remembered that a driver obtains detailed visual information around the center of the fixation point (circular area, visual cone). The size of this visual circular area is dependent upon how fine the visual detail that needs to be obtained is, and how much detailed information is contained in that circle. For very fine visual information and a large density of such information around the fixation point, the diameter of such a visual cone can be from less than 1 degree to a few degrees. Information regarding larger objects (if they are sufficiently conspicuous) will be picked up by the visual system outside this visual cone and if of interest to a driver, will most likely trigger a movement of the eyes to this object (saccade) with a subsequent eye fixation or several subsequent eye fixations to acquire, process and verify the visual information at a detailed level within a driver's expectation and memory framework.

The recommendation, "Center on the travel path" (4) is fairly well supported by the spatial results published in (9) which indicate a single mode (largest number of fixations in a $1^\circ \times 1^\circ$ cell) located at $x = 0.5^\circ H$ and $y = -0.5^\circ V$ for tangent sections (from focus of expansion, mostly on the road surface ahead) and at $x = 14.5^\circ H$ and $y = -1.7^\circ V$ for a 240 feet radius right curve (from imaginary focus of expansion, mostly on the illuminated curve surface ahead). However, these modes contain only about 13.5 percent and 3.9 percent of the total number of fixations for straight road and curve driving respectively which indicates that even though the drivers have a relatively large number of fixations at one point, a larger percentage of the fixations are spread around the mode cell and many of them on the travel path. "Scan and search the traffic scene" as explained in (4) is again similar to "Keep your eyes moving" and thus is partially validated by the results of the
E.F.S. analysis and the results published in (9). "Check mirrors and instruments" (4) is a useful recommendation especially before slowing down, stopping, or changing direction. However, based on the results in (9), mirrors and instruments were looked at very infrequently during straight road driving and practically never while driving through a curve at night since very few slowing down, stopping and changing direction maneuvers were executed.

"Look at each event in the traffic scene briefly" (4) is also similar to "keep your eyes moving" and can be partially validated by the results of this study, the cumulative fixation duration frequencies and the results published in (9). "Scan darkened areas when driving at night" (4) is very vague in terms of specific scan locations. This recommendation cannot be supported by the spatial results given in (9) which indicate that drivers have a large portion of their eye fixations within or close to the illuminated pavement surface of the curve at night or on the road pavement surface ahead. "Look at the edge of the pavement ahead of your car until the oncoming vehicle has passed" is also a general recommendation which lessens the likelihood of being temporarily blinded by the glare of the oncoming car's headlights. While this rule appears reasonable and most likely useful, there was no opposing traffic present in the immediate next lane on the straight road sections (4 - lane highway) or in the curve (one directional exit ramp) to investigate the validity of this rule.

"Center on a target 12 seconds ahead" (5) is one of the few recommendations in which the authors make a clear distinction between straight section and curve driving although nothing was mentioned about night driving. The results of the E.F.S. analysis and the spatial results given by (9) indicate clearly that a driver cannot consistently center on a target 12 seconds ahead. Again, the same comments as discussed before with regard to the "aim high at steering" recommendation would apply here. "Keep your eyes scanning and searching" (5) is again similar to "Keep your eyes moving" and the same comments as made before apply. "Take quick glances across the curve to identify oncoming traffic" is somewhat supported by the by the spatial eye fixation results shown in (9) especially for
curve driving at night which indicate that drivers do make once in a while eye fixations across the curve. Again, it should be noted that the curve in the experiment was one-directional and precluded opposing traffic which could represent a potential hazard.

"Orderly visual search pattern" (5) is a process in which drivers are recommended to search critical areas in a regular sequence. An example of this process is "glance ahead, check rearview mirror, glance ahead again, search the sides of the roadway intersections, glance ahead again, check speedometer and gauges, and glance ahead again". The results of the E.F.S. analysis do not indicate any systematic eye fixation patterns when driving through a curve which would indicate that drivers would acquire visual information through such an orderly sequential search pattern. "Selective seeing" is explained as a process of selecting and identifying only those events and clues that pertain to a driving task. Although, one would hope that drivers would follow a selective seeing procedure there was no objective way to investigate whether or not the drivers who participated in the study used such a selective seeing procedure. Moreover, it should be reiterated that the results of the E.F.S. analysis do not show any consistent pattern of eye fixation sequences from run to run within a driver and between drivers which in turn could be used to suggest a consistent selective seeing process. One might question whether the spatial and temporal eye scanning behavior results between daytime and nighttime (under lowbeam illumination) are much different from each other. A comparison with daytime eye scanning results for straight road driving given by Zwahlen (10) indicate rather small differences between the eye scanning behavior of drivers during daytime and nighttime straight road driving, with the only exception that the daytime horizontal eye fixation dispersions are somewhat larger than the nighttime horizontal eye fixation dispersions (daytime horizontal stdard deviation = 2.45°, nighttime standard deviation = 1.92°). Further, Zwahlen (11, 12) provides temporal eye scanning behavior results (averages and standard deviations of fixation durations when looking at curve warning signs, Stop Ahead and Stop signs) for day and night driving which indicate that there is no consistent trend in terms of average fixation
durations between daytime and nighttime driving.

Overall, a few general recommendations or rules with regard to eye scanning behavior when driving through curves or when driving in general such as "aim high at steering wherever and whenever possible or feasible" might be helpful (for straight road driving, when approaching a curve, when driving through a curve, etc.) to a novice driver. However, it would be highly desirable that the need for such rules as well as the conditions for which they apply would be carefully researched and justified and that such rules would be carefully developed and validated based upon driver eye scanning behavior studies conducted in representative driving environments under representative conditions with a sufficiently large group of representative drivers.

REFERENCES


The Effects of Moderate Heat on Driver Vigilance in a Moving Vehicle

David P Wyon
B A, M Sc, Ph D
National Swedish Institute for Building Research
Sweden

and

Fredrik Norin
M Sc, M E
Volvo Car Corporation
Sweden
THE EFFECTS OF MODERATE HEAT ON DRIVER VIGILANCE IN A MOVING VEHICLE

D.P. Wyon & F. Norin
Volvo Car Corporation, Göteborg, Sweden

ABSTRACT
Eighty three experienced drivers, evenly distributed over the age range 25-65, each drove for one hour over a pre-determined route in the provincial Swedish town of Gävle. 51 were men, 32 were women. The age distribution was the same for each sex. Each subject was randomly assigned to one of two thermal conditions: 21° or 27°C. The conditions alternated throughout each day, and all took place in daylight, between the hours of 8-20, in May 1990. The route included sections limited to 50, 70, 90 & 110 Km/hour. It was partly through the town, including 7 traffic lights, and partly on the motorway bypass and its approach roads. All subjects completed at least 4 circuits. The vehicle was a 1989 Volvo 760 Estate with a 4-cylinder, turbo-intercooler engine and a 4-speed automatic gearbox. It appeared normal to the subjects, but was in fact modified so that 21 different signals could be given, all of the kind a driver must monitor: warning lights, changes in the reading of the instruments, spontaneous operation of some of the controls, extraneous noises at front or rear, flashing blue lights visible in the rear-view mirrors only. Subjects were told about possible signals only in a very general way. They were instructed to press a foot-button with the left foot (not used to drive the car) if they observed anything unusual, and report it verbally before they released the foot-button. Signals were removed if unobserved for 180 seconds. A computer administered the signals, which occurred randomly with equal probability, each preceded by a delay of random length from 30-180 seconds following a response or failure to respond. The computer recorded response times and missed signals, and subjects' verbal responses were subsequently analysed from tape. In spite of large inter-individual differences, and large variability in response due to different traffic conditions, there were significant negative effects of moderate heat on vigilance. The overall proportion of missed signals increased by 50% at 27°C, and response times increased by 22%. These effects were most marked in the second half hour, for men, for subjects under 40 years old, and at speeds below 60 km/h, i.e. in city traffic rather than on the open road. The decline in vigilance at 27°C was most marked for the more peripheral signals: RPM bias, mechanical noise, police lights behind. Actual driving errors were observed significantly more often at 27°C for women.

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1. INTRODUCTION

Recent advances in the assessment of vehicle climate (Wyon et al. 1989) make it possible to state that drivers are exposed to a considerably higher degree of thermal asymmetry than that encountered in other work-places where similarly complex tasks are performed. In most vehicles it is relatively easy to adjust the average temperature so as to achieve the correct total heat loss from the body, with the exception of non-air-conditioned vehicles in hot weather, but in all cases the application of cooling or heating power to the body of the driver involves asymmetry: some parts of the body are exposed to excessive cooling, others to inadequate cooling. In order to protect the coldest parts of the body, it is very common for drivers to select an average temperature that is several degrees higher than would be required to achieve the correct total heat loss, which is equal to the rate of heat production in the body without perspiring. This preferred bias is observed even in cold weather, and increases with increasing asymmetry. It has been shown that very high levels of heat stress (32°C WBGT, causing profuse perspiration and a marked and progressive increase in pulse rate) leads to reduced rear-view mirror vigilance and an increase in "moving violations" as defined in the US police code (Mackie et al. 1974), but similar effects have never been demonstrated at the very moderate levels of heat stress of interest in the present connection, which are below the perspiration threshold. Moderate heat stress has often been shown to have adverse effects on mental performance, generally causing a decrease in arousal and reduced work-rates (Wyon 1986). It is by no means certain that the same effects would be observed on the task of driving a vehicle: whereas it is possible to relax in moderate heat in a stationary work-place, in order to reduce muscle tension and metabolic rate, the driver of a vehicle is constantly aware that relaxation is dangerous. Even quite moderate levels of heat stress may therefore have an initial arousing effect, as the driver exerts effort to avoid relaxation, followed by increasingly frequent but brief episodes of involuntary relaxation (lapses of attention) as fatigue makes it impossible to continue to counteract the relaxing effect of the heat. Raised arousal is known to reduce attentional fields, and to concentrate attention on the primary aspects of a task.

2. METHODS

In examining the effects of moderate levels of stress on a complex task, the attitude of the subject to the task is critical. This is particularly the case where the assignment of attention to multiple sources of information is expected to be altered by the stress applied. The main difference between a simulated driving task and a real one is the presence of danger to the subject in the latter case. This enforces a realistic assignment of attention between the different aspects of the driving task. In a simulated task it is possible for the subject to grossly distort his attentional field in order to improve his performance on some aspect of the task that is normally unimportant, with no penalty. In a moving vehicle, in real traffic, the subject must assign attentional priorities optimally in the interests of his own safety. It was, therefore, decided to carry out the experiment in an apparently unmodified vehicle, at normal speeds and in actual traffic. The assignment of attention to essential sources of information, of varying degrees of priority, would be the dependent variable.
The primary aspects of the driving tasks, namely progressing safely over a pre-determined route without causing danger, would not be examined systematically, except by observing any overt errors committed by subjects in the course of the experiment. Subjects were to be instructed to monitor the existing sources of information in the vehicle in the usual way, with no possibility of knowing what to expect, reporting their observations verbally while continuing to drive. They were to be recruited to be representative of the experienced driving population, and to drive over a route consisting of several types of road, e.g. including city as well as open-road driving.

2.1 Vehicle:

The test vehicle was a white 1989 Volvo Estate with a 4-speed automatic gearbox and a 4-cylinder turbo-intercooler engine. It was equipped with a standard Volvo ECC air-conditioning unit (Electronic Climate Control), which was operated in the default "automatic" mode, in which the fan-speed and the air distribution are optimized by a micro-processor. If subjects adjusted the temperature, despite being instructed not to do so, they were not reprimanded, but the adjustment had no effect. A foot switch of the type once used for dip-switch operation was mounted on the floor conveniently for left-foot operation by the driver, who was instructed not to use the left foot for brake operation. The foot-switch was used to start a tape-recorder and signal response to the computer: this is described under "Responses" below.

2.2 Signals:

Although the test vehicle appeared completely unmodified to the subjects, it was possible for an on-board computer to alter the reading of most of the instruments, to light warning lamps, and to operate some of the controls, as follows:

Road speed: 20 km/h bias up or down
Engine speed: 800 r.p.m. bias up or down.
Clock: Alteration by one minute per second forwards or backwards.
Water temperature: Bias to maximum in red warning area.
Fuel: Progressive bias downwards to empty in c.90 seconds. Tank was always at least half full at start of a run.
Warning lamps: Brake failure; parking brake; oil pressure low.
Generator failure: All warning lamps on (as if fan belt broken).
Direction indicators: Panel lamps blink as if left or right indicators were in operation. For safety reasons, indicators were not operated.
Wipers: Windscreen wipers operate spontaneously at slow speed.
Signal horn: Horn sounds briefly and spontaneously.
Noise rear: Barely audible vibration near left rear wheel, with frequency proportional to road speed.
Engine noise: Loud vibration from engine with frequency proportional to engine speed, located just in front of driver.
Police behind: Blue flashing lights visible in each of the three rear-view mirrors, attached to outside left and right rear wing below window with magnets, and inside rear window. Operated as three different signals. Subjects were instructed to monitor all three continuously.
2.3 **Responses:**

The sole response required of the driver was to depress the foot switch, await an audible tone, report verbally at leisure while holding the switch down, then release it. In order to eliminate the possibility that the subject might spot the true signal as it was moved, and alter his verbal report accordingly, signals were not removed until the foot switch had been released. Only one signal was in operation at any time, although subjects were not aware of this limitation, nor of which signals could occur.

2.4 **Experiments:**

An observer was always present in the left rear seat during the test drive.

2.5 **Test route:**

All subjects drove at least four complete circuits of a test route that was partly through central Gävle, including seven sets of traffic lights, and partly on the E4 motorway bypass and its approach roads, a total of 14.4 km. Thus, each subject drove at least 57.6 km, and for at least one hour. On the first circuit, the observer gave all necessary instructions for following the route. On the second circuit, instructions were given only if this was clearly necessary, which was noted. On the third and fourth circuit, no instructions were given unless the subject made a wrong turning, which was duly noted, as were other driving errors attributable to inattention.

2.6 **Driving conditions:**

All tests took place between 08.00 and 20.00 during May 1990. It was, therefore, broad daylight at all times. The weather was exceptionally warm and sunny for Sweden on most days, with temperatures rising to 20°C, rather few cloudy days, and only one day on which it rained. Humidity is pleasantly low in Sweden, typically 30-40% RH in May. Traffic was light by international standards and there were no traffic jams. A speed limit of 50 km/h applies in the town, and the approach roads to the E4 include sections limited to 70 and 90 km/h. The dual carriageway of the E4 motorway itself has a speed limit of 110 km/h on the relevant section.

2.7 **Subjects:**

51 male subjects and 32 female subjects took part, all in the age range of 25-65 years old. The age of each subject was estimated by the observer to the nearest 5 years. Local bus, taxi, police and military drivers were recruited initially, then members of a local football club (to obtain more young drivers), and the staff of a research institute.

2.8 **Thermal conditions:**

Alternate test drives were carried out with ECC set-temperatures of 21°C and 27°C. As subjects were recruited at times suitable for them, they were randomly assigned to thermal condition, e.g. any cancellation or new recruitment altered the conditions to which all subsequent subjects were assigned. Alternating thermal conditions
ensured that weather and time of day affected both conditions equally.

2.9 Modified display:

In preliminary exposures it was found that the standard warning lamps were so bright that subjects never failed to notice them at once. A strip of blue plastic film was therefore fixed over the row of warning lamps. Their perceived colour was unchanged, but their intensity and contrast were reduced. The film transmitted 68% of incident light. The measured contrast of the warning lamps was reduced from 35% to 9%, making them much more difficult to perceive with peripheral vision, though still clearly perceptible when the subject looked directly at the instrument display.

2.10 Signal sequence:

The computer was programmed to select any of the 21 signals at random, with equal probability, and to impose a delay of random length, from 30 to 180 seconds, before each signal. Signals were removed after 180 seconds if no response had been made. The same signal could recur without restriction. Signals were never initiated while the vehicle was standing still, but were not removed if the vehicle stopped. Road speed was recorded at the time the signal was initiated, and at the time the response was given.

3. RESULTS

3.1 Analysis:

The verbal responses recorded by the subjects were analysed and collated with the computer records of each signal and each response as timed and recorded by the computer. It was possible to classify every signal as having been detected, or not. If detected, the response time was known to within 0.01 second. Incorrect responses led to removal of the signal, as the computer could not know that the verbal response was wrong. In these cases, the length of time the signal had been present without being detected was similarly known, and could be up to 180 seconds, at which time the signal was always removed. Irrelevant responses, including the detection of events not initiated by the computer, were classified separately, so that total responses by the subject could be used as a measure of the level of activation. It should be remembered that signals were randomly assigned, so that each signal was given once only to some subjects, two or more times to other subjects, and not at all to a substantial proportion of the subjects. An analysis that concentrates on each signal separately, must therefore neglect a large amount of the available data. It is nevertheless intrinsically interesting to know how well each particular signal was detected. In this type of analysis, all responses are treated as if they were independent, even when two or more of them are from the same subject. In view of the large effects of the current traffic situation, this is a close approximation to the truth.

For each signal, the proportion of signals missed was derived for each thermal condition. The difference was examined using the non-parametric Chi-square test or the Fisher test (Siegel 1956). Response times for detection were log-normally distributed, by inspection,
and the analysis was, therefore, performed using Student's t-test on the transformed response times. Note that each of these analyses is independent of the other: they concern different events, detected signals in the former case, undetected signals in the latter case. The next type of analysis combines them by regarding detection as better than non-detection, and therefore, rank-ordering all cases of non-detection below all cases of detection, and non-detection over any given period, as better than non-detection over a longer period. All cases of non-detection over the full three minutes are naturally ranked last. For the purpose of this analysis, a quasi-response time was derived for all cases of non-detection by adding 180 seconds to the time for which the signal had been present.

The proportion of all signals detected was calculated for each subject, together with the average response time for all signals detected by each subject. This approach has the advantage that all values so calculated are truly independent, as they are from different subjects. The total number of responses, normalised by the number of actual signals given, was also calculated for each subject. These three dependent variables were analysed for differences between thermal conditions using the Mann-Whitney U-test.

3.2 **Session values per person:**

This section sets out the analysis of the following three dependent variables, based on all signals and responses: 1) % Detections (Hits); 2) Mean RT for Detections; 3) Mean number of responses per signal (No significant effects of heat on this third dependent variable were found in any of the analyses). Tables 1 & 2 set out the overall effects of heat for the whole hour. A significantly greater proportion of signals was missed at 27°C than at 21°C (P<0.01): 24% of signals given, as opposed to 16%. This is a 50% increase in the number of signals missed. In addition, the mean response time for detection was significantly longer at 27°C than at 21°C (P<0.05): 29.28 seconds, as opposed to 24.02 seconds. This is a 22% increase in response time. At 60 km/h, the vehicle would travel 86.3 metres further on average before a signal was detected at 27°C. At 90 km/h, 129.5 metres further. The probability values are for a two-tail test, i.e. they should be halved for a test of the working hypothesis of a negative effect of heat on driver vigilance.

Tables 1 & 2 show the same analyses for each half-hour separately. There were no significant effects of heat overall in the first half-hour, although the trends were in the same direction as for the whole hour. In the second half-hour, significantly more signals were missed at 27°C than at 21°C (P<0.01): 23% instead of 12%. This means that 92% more signals were missed at 27°C than at 21°C in the second half-hour. Response times for detection were significantly longer at 27°C than at 21°C (P<0.05): 28.92 seconds instead of 22.29 seconds. This means that response times for detection were 30% longer at 27°C than at 21°C in the second half-hour. In these Tables, N = Number of subjects; U = Mann-Whitney U-value; P = Probability that the observed difference could have occurred by chance.
The effect of heat on the proportion of signals missed was significant and negative when the signals were given at road speeds below 60 km/h (P<0.01), but not when they were given at higher speeds, i.e. on the open road. The negative effect of heat on response times for detection does not reach significance when the data are thus divided into two parts.

Both the subjects estimated to be below 40 years old, and those 40 and above, tended to miss more signals at 27°C than at 21°C (P<0.10), i.e. (P<0.05) for a 1-tail test of the working hypothesis of a negative effect of heat, as opposed to an unspecified effect of heat on performance. The effect of heat on response times for detection was significant for those below 40 only (P<0.05). It was negative, i.e. they responded 33% more slowly at 27°C than at 21°C. Both previously noted negative effects of heat were significant for men (P<0.05) for a 1-tail test, but not for the smaller group of women taken separately.

The effect of heat on the proportion of signals missed by male subjects was significant and negative in the second half-hour (P<0.01), but not in the first half-hour.

The negative effect of heat on response times for detection by female subjects was significant in the second half-hour (P<0.05) for a 1-tail test, but not in the first half-hour.

For subjects under 40 years old, there was a significant and negative effect of heat on the proportion of signals missed in the second half-hour (P<0.01), but not in the first half-hour. For these younger subjects, the effect of heat on response times for detection was significant (P<0.01) and negative in the first half-hour, but not in the second half-hour. For older subjects, the effects of heat in each half-hour taken separately did not reach significance for a 2-tail test.

Further analyses on these lines show (1) that the effect of heat on the proportion of signals missed was significant (Z = 2.45; P<0.01) and negative for male subjects at speeds below 60 km/h, but not at higher speeds or for females at either speed; (2) that the effect of heat on the proportion of signals missed was significant (Z = 2.88; P<0.01) and negative for subjects under 40 years old at speeds below 60 km/h, but not at higher speeds, or for subjects aged 40 and over at either speed; and (3) that the effect of heat on the proportion of signals missed at speeds below 60 km/h was significant and negative in the second half-hour (Z = 2.92; P<0.01), but not in the first half-hour, and not at speeds above 60 km/h.

3.3 Each signal separately, non-detection taken as long response time:

Rank-ordering non-detection below detection as described for each signal, the following results were obtained using the Mann-Whitney U-test (1) A significant negative effect of heat on attention to an unexpected noise at left rear wheel (30 signals at 21°C, 22 at 27°C U = 178.5; Z = 2.81; P<0.01); (2) A significant negative effect of heat on attention to the three warning lamps taken together (113 signals at 21°C, 105 at 27°C; U = 4790.5; Z = 2.45; P<0.01); (3) A significant negative effect of heat on attention to the brake failure warning lamp (37 signals at 21°C, 30 at 27°C; U = 381.5; Z = 2.19; P<0.05);
(4) A significant negative effect of heat on attention to the clock running fast (29 signals at 21°C, 36 at 27°C; U = 361; Z = 2.12; P<0.05); (5) A tendency for heat to reduce attention to the oil pressure warning lamp (47 signals at 21°C, 35 at 27°C; U = 617; Z = 1.93; P<0.10); and (6) A tendency for heat to reduce attention to the RPM-indicator reading too high (46 signals at 21°C, 54 at 27°C; U = 976; Z = 1.84; P<0.10). When these analyses are repeated for each half-hour separately, thus reducing the amount of data available for each comparison, the only significant results (P<0.05) are found in the second half-hour: for warning lamps together, noise at rear wheel, and clock running fast, respectively, ordered according to their level of significance.

3.4 Each signal separately, proportion detected:

For all subjects during the whole hour.

Noise at rear wheel: 4/30 (13%) missed at 21°C, 9/22 (41%) at 27°C; Chi-square = 5.15 (P<0.05)

RPM high: 32/46 (70%) missed at 21°C, 50/54 (93%) at 27°C; Chi-square = 8.92 (P<0.01)

Horn: 1/41 (2%) missed at 21°C, 4/24 (17%) at 27°C; Fisher 1-tail P = 0.0578

Fanbelt: 2/48 (4%) missed at 21°C, 8/39 (21%) at 27°C; Fisher 1-tail P = 0.020

Police L.R: 0/85 missed at 21°C, 10/67 (15%) at 27°C; Fisher 1-tail P = 0.0002

Warning lamps: 0/113 missed at 21°C, 10/105 (10%) at 27°C; Fisher 1-tail P = 0.0005

Similar results were obtained in each half-hour considered separately.

3.5 Each signal considered separately, response time for detection:

The effect of heat was examined using Student's t-test on the log-transform of the response times for all subjects during the whole hour. Only response times to the BRAKE FAILURE lamps were significantly affected by heat in a 2-tail test (P<0.05): they were slower at 27°C than at 21°C. There were no significant effects in the first half-hour. In the second half-hour, men were significantly slower to respond to NOISE AT REAR (P<0.05) at 27°C than at 21°C, and women were significantly slower to respond to the OIL PRESSURE LOW lamp (P<0.05) at 27°C than at 21°C.

3.6 Observed driving errors:

Five women made a wrong turning during the third or fourth circuit. One woman failed to observe that traffic in front had stopped and had to use the ABS-brakes to avoid a collision. All six were driving at 27°C. Thus, 6/18 (33%) were observed to make a driving error caused by inattention at 27°C, 0/14 at 21°C: Fisher 1-tail P = 0.020,
i.e. \( P < 0.05 \) for the negative effect of heat on driving errors made by women. Only one male subject made such an error, also at 27°C, which is naturally not significant. Further, two women were prevented at the last minute from making a wrong turning during the second circuit. They were also driving at 27°C. Thus, driving errors due to inattention were observed in 7/18 (39%) of women at 27°C, 0/14 at 21°C: Fisher 1-tail \( P = 0.0095 \), i.e. \( P < 0.01 \) for women in circuits 2-4. One woman did in fact make wrong turns during circuits three and four, despite having been prevented from doing so in circuit two. She has been counted only as one instance in the above analysis. Two out of 23 men driving at 27°C were observed making errors of this kind during circuits 2-4, and one man out of 28 driving at 21°C; this is again nowhere near the significance level.

3.7 **Age distribution:**

54% of the estimated ages of all subjects were below 40, and the effects of heat were therefore examined separately for the groups "below 40" and "at least 40". For this to be a valid indicator of age effects, it is necessary to show that the age distribution was the same for each sex. Of 51 males, 20 were 25-30, 16 were 35-40, and 15 were 45-. Of 32 females, 12 were 25-30, 11 were 35-40, and 9 were 45-. This yields a Chi-square = 0.08, which does not approach significance. The age distribution was thus the same for both sexes.

3.8 **Thermal conditions:**

Measurements of air temperature in the vehicle on days without sunshine gave values within 0.5°C of the set values 21°C or 27°C. Thermal manikin measurements show that the ECC-unit compensates adequately for sunshine and for changes in external temperature.

4. **DISCUSSION & CONCLUSIONS**

A very moderate rise in temperature, not sufficient to cause observable perspiration in the majority of subjects and typically occurring in all non-air-conditioned vehicles for several months during the summer even in Sweden, has been shown to have significant negative effects on driver vigilance. These effects occurred in the first half-hour of driving, despite the experimental situation and the presence of an observer in the back seat. The effects were quite large: a 50% increase in the number of signals missed and a 22% slower response time to those signals that were detected.

The effects of moderate heat were more noticeable in the second half-hour, at speeds below 60 km/h, i.e. in city traffic; they were, in other words, accentuated by fatigue and by information overload, rather than by underload. The effects of heat were also more noticeable for male subjects, and for subjects aged below 40. The effects of heat would normally be expected to be greater for female subjects and for older subjects, on physiological grounds. It therefore appears to be the case that subjects were overreacting to the heat stress, rather than reducing physiological strain by lowering their level of arousal, because, in this case, information underload would enhance the effects, and those categories expected to suffer greater physiological strain would be more affected, not less.
The results are thus in accordance with an arousing effect of heat stress, as is the fact that two of the most difficult signals to detect, and the least essential to the primary task of driving, were consistently affected by heat; the barely audible noise at the rear wheel, and the upward bias of RPM.

For women, moderate heat stress also caused general lapses of attention: remembering the route and avoiding collisions are primary aspects of the driving task, yet were also impaired by heat stress in the first hour. The same effect may be expected to appear for men in heat exposures of longer duration.

5. REFERENCES


### TABLE 1
*% Detections per signal, all signals*

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>21°C N</th>
<th>MEAN</th>
<th>27°C N</th>
<th>MEAN</th>
<th>M-W U =</th>
<th>P&lt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-60 minutes</td>
<td>42</td>
<td>0.84</td>
<td>41</td>
<td>0.76</td>
<td>589.0</td>
<td>0.01</td>
</tr>
<tr>
<td>0-30 minutes</td>
<td>42</td>
<td>0.80</td>
<td>41</td>
<td>0.74</td>
<td>692.0</td>
<td>NS</td>
</tr>
<tr>
<td>30-60 minutes</td>
<td>42</td>
<td>0.88</td>
<td>41</td>
<td>0.77</td>
<td>527.5</td>
<td>0.01</td>
</tr>
<tr>
<td>0-60 km/h</td>
<td>42</td>
<td>0.84</td>
<td>41</td>
<td>0.72</td>
<td>518.0</td>
<td>0.01</td>
</tr>
<tr>
<td>60-110 km/h</td>
<td>42</td>
<td>0.83</td>
<td>41</td>
<td>0.79</td>
<td>777.5</td>
<td>NS</td>
</tr>
<tr>
<td>&lt;40 years old</td>
<td>25</td>
<td>0.84</td>
<td>20</td>
<td>0.78</td>
<td>177.0</td>
<td>0.10</td>
</tr>
<tr>
<td>0-30 mins.</td>
<td>25</td>
<td>0.80</td>
<td>20</td>
<td>0.78</td>
<td>227.5</td>
<td>NS</td>
</tr>
<tr>
<td>30-60 mins.</td>
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<td>20</td>
<td>0.79</td>
<td>147.5</td>
<td>0.01</td>
</tr>
<tr>
<td>40+ years old</td>
<td>17</td>
<td>0.84</td>
<td>21</td>
<td>0.74</td>
<td>112.5</td>
<td>0.10</td>
</tr>
<tr>
<td>Males</td>
<td>28</td>
<td>0.86</td>
<td>23</td>
<td>0.77</td>
<td>224.0</td>
<td>0.10</td>
</tr>
<tr>
<td>0-30 mins.</td>
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<td>0.82</td>
<td>23</td>
<td>0.77</td>
<td>279.0</td>
<td>NS</td>
</tr>
<tr>
<td>30-60 mins.</td>
<td>28</td>
<td>0.89</td>
<td>23</td>
<td>0.79</td>
<td>193.0</td>
<td>0.01</td>
</tr>
<tr>
<td>Females</td>
<td>14</td>
<td>0.80</td>
<td>18</td>
<td>0.74</td>
<td>92.5</td>
<td>NS</td>
</tr>
<tr>
<td>0-30 mins.</td>
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<td>0.71</td>
<td>97.5</td>
<td>NS</td>
</tr>
<tr>
<td>30-60 mins.</td>
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<td>0.84</td>
<td>18</td>
<td>0.76</td>
<td>87.0</td>
<td>NS</td>
</tr>
</tbody>
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**Fig. 1** % Missed signals
(Based on the above table)
**TABLE 2**  Mean RT, seconds, all signals

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<th>M-W</th>
<th>U =</th>
<th>P&lt;</th>
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<tr>
<td></td>
<td>N</td>
<td>MEAN</td>
<td>N</td>
<td>MEAN</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0-60 minutes</td>
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<td>24.02</td>
<td>41</td>
<td>29.28</td>
<td>618.0</td>
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<tr>
<td>0-30 minutes</td>
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<td>26.20</td>
<td>41</td>
<td>30.89</td>
<td>722.0</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>30-60 minutes</td>
<td>42</td>
<td>22.29</td>
<td>41</td>
<td>28.92</td>
<td>637.0</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0-60 km/h</td>
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<td>24.10</td>
<td>41</td>
<td>29.06</td>
<td>712.0</td>
<td>NS</td>
<td></td>
</tr>
<tr>
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<td>162.0</td>
<td>0.05</td>
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<tr>
<td>40 + years old</td>
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<td>21</td>
<td>29.03</td>
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<td>32.00</td>
<td>241.0</td>
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<tr>
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<td>NS</td>
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<tr>
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<td>18</td>
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<td>18</td>
<td>35.60</td>
<td>76.0</td>
<td>0.10</td>
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</table>

**Fig. 2**  Mean RT  
(Based on the above table)
Position Accuracy when Pushing Pushbuttons in a Car as a Function of Car Speed and Location: Implications for Design

Helmut T Zwahlen
Department of Industrial and Systems Engineering
Ohio University
USA

and

David Kellmeyer
Department of Industrial and Systems Engineering
Ohio University
USA
POSITION ACCURACY WHEN PUSHING PUSHBUTTONS IN A CAR AS A FUNCTION OF CAR SPEED AND LOCATION: IMPLICATIONS FOR DESIGN

Helmut T. Zwahlen and David Kellmeyer

Department of Industrial and Systems Engineering
Ohio University, Athens, Ohio 45701-2979
(614) 593-1550
ABSTRACT

The need for more push buttons and other finger or hand activated types of controls on automobile dashboards, steering wheels, stereos and in-car communication systems has increased over recent years. Further increases in the number of push button and/or other finger and hand activated types of controls are expected in the future with the emergence of new, sophisticated driver aids and IVHS technology. The area to place these controls within a driver’s reach envelope has remained fairly constant or has actually shrunk due to the down sizing of cars and the addition of crash protection devices. A good example of this trend are today’s in-car entertainment systems (combined radio, tape deck, compact disc player, equalizer, etc.) where designers are forced to design smaller push buttons and other types of controls and to place these buttons and/or controls closer together in order to fit them into the allotted area along with the accompanying displays. With designers reducing the button sizes and compacting them together, the driver is forced to devote more time and concentration to activate the correct buttons. This could impose many safety problems if too much time and concentration are diverted from the driving task. The objective of this study is to examine some of the human factors issues and their design principles as they relate to the design of push buttons in terms of the shape, size and spacing.

The first part of this study investigates a driver’s accuracy when pushing buttons located at three different positions along the longitudinal center-line of the car, while either stationary or driving at approximately 20 mph. Twelve, young drivers (average age of 21.6 years) were used to determine how closely they could push with their index finger to the center of a cross-hair target located at these three different positions (0°-dashboard height, 45°-stereo position and 90°-between the front seats) for both the static and dynamic conditions. For each trial, the drivers had to move their right hand from the steering wheel and attempt to hit a cross-hair target using their right index finger which was fitted with a pin-point marking device. The dynamic condition was conducted while driving along a straight, smooth airport runway. The order of the presentation was balanced for the static and dynamic conditions and randomized for the three push-pad positions. Thirty trials were conducted for each position under both static and dynamic conditions. This data provided the basis to construct scatterplots for the horizontal and vertical accuracy achieved under the different experimental conditions. These values were then converted into polar miss distances.
for further study.

Our results show that for the conditions investigated a circular push button offers a nearly optimal design shape because the horizontal and vertical miss standard deviations proved to be approximately equal (each scatterplot closely resembled a circular pattern). This circular approximation holds except in cases where there is excess motion or vibration in either the vertical or horizontal directions. Secondly, the middle or stereo position provided the greatest accuracy in each condition.

The second part of this study developed cumulative probability curves for hit rates as a function of the radius for each speed and position and combined this with index finger-tip dimensions to develop a design methodology. This methodology allows a designer to determine the size and spacing of push buttons to obtain a desired confidence of hitting the correct button while avoiding any inadvertent hits of adjacent buttons at a selected confidence level. The designer needs only to specify these confidence levels and the population to be covered along with the percentage of the finger-tip width required to activate the button. These design rules and look-up tables have been translated into a PC program that allows the designer to choose these parameters and then outputs the optimal button dimensions and spacing. This program is also useful to evaluate existing push button designs.

INTRODUCTION

Prior to conducting this study a literature review was conducted on relevant findings concerning push button operation. Deininger [1] investigated push button size as a variable in different keyboard arrangements. In his experiment, he found out that by increasing the dimensions of a square button from 9.5mm to 17.4mm, a considerable reduction was observed in keying times from 6.35sec to 5.83sec and errors (hitting adjacent buttons) were reduced from 7.1% to 1.3%. Chambers and Stockbridge [2], reported that speed and accuracy were important considerations in activating a push-button, that is, to direct the finger accurately at the appropriate button and to hit the button as quickly as possible. They showed that push-buttons were the most efficient controls in terms of operating speed but less accurate because of its ballistic-like movement. Droege and Hill [3], demonstrated that variations in button resistance can have
important implications for performance. Moore [4] suggested a range for push button resistance of 283g to 1133g if one finger is used, 140g to 560g if different fingers are used and also suggested that the diameter for push buttons for finger-tip activation should be between 10mm and 19mm. Noting that finger dimensions are the limiting factors with respect to push button size, Garrett [5] provides a number of anthropometric dimensions for different parts of the adult hand. Sanders and McCormick [6] have cautioned that the usefulness of any control can be limited by such features as its size and location, its relationship to the appropriate display and the type of feedback which it gives to the operator.

It is our finding that previous design specifications for push button controls have been established for fairly specific and simple situations and have not taken explicitly into account such factors as the push button location and/or the presence of motion and vibration. Also, these previous design guidelines assume a standard size for all push buttons regardless of the confidence required for hitting a given push button. This means that the size of a push button is independent of the consequences of missing that button or hitting an adjacent button. This seems to be a major flaw in present push button guidelines and the following paper proposes an alternate means of proposing push button shape, size and spacing guidelines. Another key issue is the use of the dead space between the individual push buttons to minimize the chance of hitting an adjacent button and to maximize the use of the available space. The proper use of this dead space as explained in this paper can reduce the space requirements of a push button control panel without affecting its performance.

METHOD

Subjects

In this study, a group of twelve college students was used. There average age was 21.6 years with a standard deviation of 2.1 years. On the average they had 5.6 years of driving experience with a standard deviation of 2.8 years. Of the twelve subjects eight were males, four were females and all twelve were right handed. The differences in accuracy between subjects can be seen in Figure 1 where two of the subjects can be seen as missing the cross-hair center considerably more than the others. There was no reason to believe that this was due to anything
FIGURE 1 Subject Performance as a Function of the Average and Standard Deviations of their Polar Miss Distances in Millimeters for all conditions.
but normal population variance, so that the data of all the subjects was included in the results.

**Experimental Site and Apparatus**

A 2000 ft long by 75 ft wide unused, concrete airport runway was used as the experimental site. The runway was level and relatively smooth. This site was chosen in order to avoid large variability in the roughness of the roadway and to operate in a safe driving environment. The experimental car was a 1986 Chevrolet Chevette equipped with a standard transmission. The push pads consisted of wood mounting devices that were covered with a thin foam pad to simulate an actual push (see Figure 2). These push pads had picture frame hooks attached to them to allow the push card targets to be easily attached and removed. These push card targets (see Figure 2) showed a computer drawn cross-hair (+) which simulated the center of a push button. The front of the card had spaces to record the X and Y miss distances, while the back of each card denoted the subject, speed, etc. of that push. The cards had two holes on the top to facilitate easy hanging and removal from the mounting device. In order to obtain a precise and consistent determination of a subjects push location, a marking device was mounted on the subject’s right index finger. This device was made of a sharp wire, the point of which was aligned on the center of the index finger and attached to the finger using a bracing ring and sports tape (see Figure 3). The point of the marking device only protruded slightly so as not to affect a subject’s accuracy by hitting the target too far before the actual finger would have touched.

The push pads were mounted in the car in three locations along the longitudinal axis of the car. Figure 4 shows the the three locations as the top position (dashboard level, horizontal push), the middle position (stereo level, 45 degree push) and the bottom level (seat level, vertical push).

**Experimental Design**

The dependent variables in the study were the miss distances in the X and Y directions to the nearest half millimeter (later these were converted into a single polar coordinate dependent variable). Our margin of error for determining the push location was about +/- 0.25mm. The independent variables of interest in this experiment were button position (the three push pad locations) and the car speed (0 mph and 20 mph) which were both considered as fixed variables.
Figure 2 - (a) Push card mounting devices, (b) Push card target
FIGURE 3 - Push pin marking device
FIGURE 4 - Cut-away side view of push pad positions
The push positions were balanced so that in three pushes each position would occur once in a random order. This was done to ensure an equal number of pushes for each position at each speed. The subjects alternated between which speed to begin with and ran all the trials for that speed in succession. Other independent variables that were thought to cause some variations were the subjects, time between pushes, the learning rate, road surface and car type. The subjects were chosen randomly among the college population. The time between pushes was randomized between 5 seconds (the minimum time to change a push card) and 15 seconds. The learning rate was combated by balancing the number of subjects that began with the static and with the dynamic condition. The road surface and car type were rigidly controlled by using the same experimental roadway and car during the whole experiment.

A split-split-plot design was elected to deal with not randomly alternating between static and dynamic conditions with each push and to deal with having to run each subject during different days. The randomization scheme used to run the experiment was using the subjects as repeated measures and using a balanced design to determine which speed each subject started on. The positions were balanced within each speed and there were 30 replications for each speed by position condition.

Experimental Procedure

Once equipped with a marking device on the index finger, the subject was told to begin either with the static or 20 mph condition. For each condition the subject sat in the driver's seat, one experimenter sat in the passenger seat to change the push cards and another experimenter sat in the back seat to call out which push pad location the subject was to press (see Figure 5). Each subject was to perform a total of 30 pushes for each of the three push pad positions during both the static and dynamic conditions. Thus, each subject was to perform a total of 180 (30x3x2) pushes which took an average time of about one hour.

For each speed, the experiment started by the experimenter in the back seat calling out the position to be pushed according to a random time sheet. The subject then pushed this location, returned his hand to the wheel and waited for the next position to be called. During this time, the experimenter in the passenger seat removed the used card, placed it in a stack and replaced it with a
FIGURE 5 - Top view of subject/driver and experimenters locations
new card. This was continued until 30 pushes were obtained for each position and then the data for the remaining speed condition was collected.

Before beginning each speed, the subjects were allowed 3 to 6 practice pushes to familiarize themselves with the three locations. During the static condition, each subject was requested to be concerned with two factors: keeping both hands on the steering wheel until told to push and pressing the correct push pad. For the dynamic condition, each subject drove around the runway a couple of times to become familiar with the car and with maintaining the 20 mph speed. The subject was then told to be concerned with three factors: maintaining both hands on the steering wheel until told to push, pressing the correct push pad and maintaining the 20 mph speed. During the dynamic condition, pushes were only called while on the straight stretches.

RESULTS

X & Y Coordinate Results

For each push, the distance of that push from the center of the cross-hair was recorded in millimeters for both the X (horizontal) and Y (vertical or longitudinal) directions. Every subject’s pushes where then combined and grouped into the six speed by position combinations. From this a scatterplot was developed for each speed by position combination. Each scatterplot of 360 pushes showed a distribution that was approximately, uniformly spread around the center of the cross-hair in a circular pattern (see Figures 6-11). From this preliminary observation, it appeared that people hit the target accurately around the center position. By looking at the average X and Y misses in Figure 12, it is seen that this is fairly true for the horizontal direction and this was confirmed as the average horizontal miss was not significantly different from zero. However, the average vertical miss for all conditions was -0.66mm which was significantly different from zero and outside of our +/-0.25mm margin of error for measurement. This slight miss in the vertical direction could be attributed to the positioning of the marking device on the finger or that people generally miss slightly below a target indicator. If the latter is true, buttons should be designed with a target indicator located just above the center of a push button.

From the observation that the points in the scatterplots resembled fairly closely a circular pattern, a hypothesis was developed that a circular button would provide the optimal push button
FIGURE 6 - Scatterplot of all pushes at the bottom position at 0 mph
FIGURE 7 - Scatterplot of all pushes at the bottom position at 20 mph
FIGURE 8 - Scatterplot of all pushes at the middle position at 0 mph
FIGURE 9 - Scatterplot of all pushes at the middle position at 20 mph
FIGURE 10 - Scatterplot of all pushes at the top position at 0 mph
FIGURE 11 - Scatterplot of all pushes at the top position at 20 mph
FIGURE 12  Average Miss Distance in Millimeters for the X and Y Directions as a Function of Speed and Position
shape for the conditions investigated. To verify this, the X and Y standard deviations were compared for the different speeds, positions and speed-position combinations. However, the statistical results showed that the miss distances in the X and Y directions were significantly different in all cases. It should be noted that with the large number of trials the criteria for a significant difference was very small, less than the precision of our measurements. By looking at Figure 13, it is seen that the X and Y standard deviations are extremely close for all positions at the 0 mph condition, neither exceeding the other by the +/-0.25 mm measurement error. Furthermore, the 0 mph condition does not show a pattern of the X or Y deviation being greater for each position. This leads to the conclusion that for the static condition a person will miss a target in a circular pattern of approximately the same radius for each position and thus a circular push button would provide the optimal shape. This can be also be seen by noticing that the distribution for each position’s 0 mph scatterplot is approximately equal.

If the 20 mph case is observed in Figure 13, a distinct pattern is seen with regards to the Y-variation being consistently slightly higher than the X-variation for each position. This difference is below the margin of error except for the bottom position but in any case the pattern is consistent. From this, it was concluded that the motion of the car in the vertical direction produced this greater variation in the Y direction. This would mean that an elliptical button instead of a circular button would be optimal in the presence of motion, but only if there was an excessive motion in either the vertical or horizontal directions and not both because they would then each produce a greater variation in their respective directions.

Another interesting trend in Figure 13 is that with the addition of speed the standard deviations are no longer approximately equal for the three positions. It appears that the standard deviations in both the X and Y directions are minimized at the middle position and the bottom position provides slightly better results than the top position. Again, this observation is also apparent from looking at the distributions of the scatterplots. This could be explained through simple mechanics since the arm must be extended further to hit the top button compared to the middle button and is thus more susceptible to movements from the car. However, this theory does not hold true for the middle and bottom positions.

It is left to the designer to decide which of the above information is relevant to his or her
FIGURE 13 - Standard Deviations of Polar Miss Distances in Millimeters for the X and Y Directions as a Function of Speed and Position
situation. Once this is done he or she can use the simple geometric equations for a circle or an ellipse to design the optimal push button. In the circular design, the X and Y standard deviations are assumed equal and thus combined into a polar dimension. The average misses in the X and Y directions can still be used if desired to center the button around a target properly (in the findings above there was an average miss for all pushes of -0.66mm in the Y direction).

The equation for a circular push button would appear as such:

\[(x-h)^2 + (y-k)^2 = r^2\]

- \(h\) = average horizontal miss (from our results \(X_{avg} = 0\))
- \(k\) = average vertical miss (from our results \(Y_{avg} = -0.66\))
- \(r\) = the polar radius required to achieve a desired hit rate, given by the polar miss standard deviation

For an elliptical button the same notations would apply but it is assumed that the X and Y variations are no longer equal. The equation for an elliptical push button would be as follows:

\[(x-h)^2/a^2 + (y-k)^2/b^2 = 1\]

- \(h\) = average horizontal miss (from our results \(X_{avg} = 0\))
- \(y\) = average vertical miss (from our results \(Y_{avg} = -0.66\))
- \(a\) = radius in the X direction to achieve a desired hit rate, X standard deviation
- \(b\) = radius in the Y direction to achieve a desired hit rate, Y standard deviation

The horizontal (a), vertical (b) and polar (r) radii required to achieve a desired hit rate can be computed through using the known variations in the data and the development of cumulative probability curves for the hit rates at given radii. This is developed in more detail later in this paper.

Polar Coordinate Results

If the differences in the X and Y standard deviations are considered negligible, the X and Y coordinates can be converted into a single polar coordinate that can then be used more easily to develop push button designs. This is a valid assumption for the static case and for all practical purposes the 20 mph case. Thus, polar coordinates will be used to show the effects of speed and position and to ease in the development of a push button design methodology (for those wanting to use the X, Y coordinates, the following discussion holds except that the a and b terms in the
elliptical equation must be computed separately in the same manner as the polar radius will be here).

The analysis of variance for the polar miss distances is shown in Table 1. The strongest factor was the differences in the subjects' pushing ability. Of the controlled factors, speed was found to be more significant than the push button position, with speed significant at the 5% level and position only significant at the 10% level. The combined affect of speed and position does not seem to be significant with the same trend of the middle position being better occurring at each speed. It also will be seen later that the speed-position effect does affect the standard deviation of the polar miss but not the average and this would thus not be apparent in an ANOVA table.

Figure 14 shows the average miss distances in polar coordinates as a function of both speed and position. The average polar miss distance increases (the accuracy decreases) for each position with the addition of speed. The motion caused a decrease in accuracy of 16% for the middle position and a decrease of 20% for the top and bottom positions. The middle position appears to be slightly more resistant to the decreases in accuracy caused by motion. Another distinct pattern in Figure 14 is that for each speed the middle position provides the greatest accuracy followed by the bottom and then the top positions. As one moves from the middle to the bottom position a 10% decrease in accuracy is seen for each speed and a further 5% decrease is observed when moving from the bottom to the top position. This accounts for a 15% decrease in a person's accuracy from the middle to the top position for each speed. The conclusion is that the middle position provides the best accuracy and this is amplified with the addition of motion since the accuracy at the middle position is least affected by the addition of motion.

When trying to determine the smallest size button required to achieve a desired hit rate, not only is the accuracy (polar average miss) important but also the variation of this polar miss (polar variation) is important. The goal is to find the position that provides the greatest accuracy and the minimum variation. These are the same principles used by Tagguchi to improve manufacturing production processes by making them less susceptible to environmental variations (such as speed and the subjects). Figure 15 shows the standard deviations of the polar miss distances for each speed and position. From this figure it is apparent that for the static condition the variation is the same for all positions. However, under the dynamic condition not only do the standard deviations
TABLE 1 ANOVA Table for the Polar Miss Distances

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<td>237.8</td>
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<td>5.07**</td>
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<td>16.09</td>
<td>MS(Error)</td>
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<td>Speed*Sub</td>
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Pos = Position
Sub = Subject
*** = Significant at an alpha of 1%
** = Significant at an alpha of 5%
* = Significant at an alpha of 10%
Figure 14 - Average Polar Miss Distance in Millimeters as a Function of Speed and Position
FIGURE 15 - Polar Miss Standard Deviations in Millimeters as a Function of Speed and Position
become greater but they no longer are equal and have again reverted back to the middle position providing the best results followed by the bottom and then top positions. Thus, when faced with motion, not only is the middle position the best in terms of accuracy but also in terms of variation.

DISCUSSION OF RESULTS

People on the average are very accurate in centering their pushes around a target indicator (cross-hair) and thus some type of symmetrically shaped button will be optimal for the conditions investigated in this study. For the static condition, the variations are not only symmetrical, but circular and thus a circular button will prove optimal. This is also true of the 20 mph condition for all practical purposes, which means a circular button will still prove to be nearly optimal under this condition. Furthermore, in our study pushes were only done while driving on straight sections and thus motion resulted mainly from the fluctuations of the car in the vertical direction. In curve driving situations, horizontal motion will also occur and in a presently ongoing experiment this appears to provide very similar effects as the vertical motion but in the horizontal direction. This will mean that a circular button may still prove optimal if one expects the majority of driving situations to produce motions in both horizontal and vertical directions.

The objectives of this study were to determine the optimal shape, size and spacing of a push button control system to achieve a desired performance while using a minimum amount of space. This was to be done for both 0 and 20 mph and for the three different positions. In the process, it was found that the middle position provided the best accuracy for both speeds and the smallest variation under the dynamic condition. A round button was determined as providing the optimal shape for the conditions investigated unless a greater vehicle motion was present in vertical direction. Any other choice of button shape will either compromise a person’s performance, or take up more space.

The optimal size and spacing of push buttons for a desired performance level can be determined by computing the cumulative number of hits as the radial dimension of the button is increased for each speed-position combination. These cumulative probability curves are shown in Figure 16 and provide the designer with the required radial dimension to achieve a given hit rate. Figure 16 shows the six curves for all speeds and positions investigated in this study, thus
FIGURE 16 - Cumulative hit rate curves as a function of the radial dimension in mm for all position and speed combinations.
showing the effects of both speed and position. One should realize that the size of the finger-tip used to press the button is a major factor when determining push button size and spacing, along with, the percentage of the finger-tip width required to activate the button. A method for accounting for both of these factors will be explained in the following section. For now, it is important to realize that the polar distances in the experiment represented the distance from the center of the cross-hair to the middle of the index finger-tip. This measurement is what was used to compute the curves in Figure 16 and should not be used to design any push buttons without accounting for at least the finger size.

The reason this data should not be used without adjustment is because the data assumes three major factors: that aiming at a button is like aiming at a finite target (cross-hair), a pin-size finger-tip is being used and that half of the finger is required to activate the button (since the marking device was located in the center of the finger-tip). The first assumption is valid because when aiming for a button people generally aim for the center but the others need adjustment.

**Finger-Tip Width Adjustment**

The second assumption will now be adjusted to depict the full finger-tip width being utilized, not just the center point. As the width of the finger-tip increases, the required button size decreases and the required spacing between adjacent buttons increases. After the following conversion, the assumption is changed to that any touch of the finger-tip will activate any button. The size requirement of this new button is obtained by subtracting half of the finger-tip width from the dimensions given in the cumulative curves as shown in Figure 17 (remember we measured out to the center point of the finger-tip). The spacing required to achieve a certain confidence that adjacent buttons will not be accidentally pushed by any portion of the finger-tip can be computed in just the opposite manner. Here, the radial dimension is determined for a given confidence level and the half-width of the finger-tip is added to this dimension (see Figure 18) to ensure that for a selected confidence level the outside of the finger-tip does not hit any adjacent buttons. It should be noted that at each position the subjects naturally used an approximately 45 degree push angle. At this angle, the finger-tip produces about a circular push pattern with a diameter approximately equal to that of the width of the first joint of the finger. Thus, this method is valid for adjusting
Adjusted button size if any part of the finger-tip width activates the button

Adjusted Button Size

Determined distance to hit a certain % of time with 50% of the finger-tip width

\[ \text{Adjusted Size} = \text{Determined Distance} - \frac{W}{2} \]

FIGURE 17 - Push button size adjustment from requiring half of the finger-tip width to activate the push button to requiring any part of the finger-tip width to activate the push button
Adjusted circular area where no adjacent buttons can fall inside if any part of the finger-tip width activates an adjacent button

Adjusted Clearance Radius \( R \) = Determined Distance + \( \frac{W}{2} \)

FIGURE 18 - Clearance radius adjustment for adjacent buttons from requiring half of the finger-tip width to activate an adjacent push button to requiring any part of the finger-tip width to activate an adjacent push button
both the vertical and horizontal dimensions. Anthropometric data for adult person (male or female) was obtained on the width of the index finger's first joint to use in these adjustments by averaging the adult male and female dimensions (1%, 14mm; 5%, 15.5mm; 50%, 16.5mm; 95%, 19mm; 99%, 19mm) [7].

Finger-Tip Percentage Required for Push Button Activation

The final assumption will be overcome by adjusting the push button size and spacing to account for different buttons requiring different amounts of finger-tip width contact to produce a hit. The greater the amount of the finger-tip width required, the larger the button must be and the smaller the spacing must be that is required between adjacent buttons. It should be remembered that in the adjustments discussed above, any portion of the finger-tip width was assumed to activate the button, if this is a proper assumption the following adjustment may be omitted. When determining the new button size requirement, the percentage of the finger-tip required to produce a hit is converted into a fraction and multiplied by the finger-tip width and added to the radial dimensions obtained from the first two conversions. If the amount of finger-tip width required for activation is not given in a percentage but rather as a dimension, this dimension can be substituted directly and added to the first two adjusted dimensions (button size and clearance radius) (see Figure 19). Figure 19 also shows the width of the finger-tip for a selected percentage of the adult person population (such as 1%, 5%, etc.) and the computed distance as a function of the desired hit rate. In order to achieve the same results for the spacing requirement, the finger-tip width for a selected percentage of the population (90%, 95%, etc.) must be subtracted instead of added (see Figure 20). These adjustment procedures are fairly simple and are usually better understood by looking at the equations accompanying the figures.

These procedures along with the radial dimension data and index finger-tip width data have been put into a FoxPro database program that allows the designer to select the desired hit rate, the desired incorrect hit rate, the lower and upper percentages of the population to be covered (used to determine finger-tip width size), the finger-tip width percentage required for activation, the dynamic or static condition along with the button position to receive an optimal push button size and spacing layout. Table 2 provides a summary of the output obtained by using the PC program.
100% of finger-tip width required
75% Required
50% Required
Any Part Required

Adjusted size of the push button is proportional to the amount of the finger-tip required to activate the button

Adjusted Button Size if a certain percentage of the finger-tip is required to activate the push button

Determined radial distance to achieve X% of hits

W is a function of the % of the population to be covered by the design

Adjusted Size = (Determined Distance - W/2) + % fingertip width required x W

FIGURE 19 - Push button size adjustment given a desired hit percentage (X%), a selected percentage of the population to be covered (W) and a selected percentage of the finger-tip width (any, 50%, 75%, 100%) required to activate the push button
Adjusted circular area where no adjacent buttons can fall inside if any part of the finger-tip width activates an adjacent button.

50% of finger-tip required

50% x W

100% x W

R

Determined Distance

W

Adjusted Clearance Radius = R - (% fingertip width required x W)

FIGURE 20 - Clearance radius adjustment for a certain percentage of the finger-tip width being required to activate an adjacent push button.
TABLE 2 - PC program results showing required push button diameters, spacing and clearances for 95% of the adult-person population using the middle position, moving at 20 mph and requiring 25% of the finger-tip width to activate the button.

<table>
<thead>
<tr>
<th>% chance of hitting the correct push button</th>
<th>90</th>
<th>95</th>
<th>98</th>
<th>99</th>
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<tbody>
<tr>
<td>10 a</td>
<td>3.05</td>
<td>7.17</td>
<td>18.99</td>
<td>25.21</td>
</tr>
<tr>
<td>b</td>
<td>15.13</td>
<td>17.18</td>
<td>23.10</td>
<td>26.21</td>
</tr>
<tr>
<td>c</td>
<td>12.08</td>
<td>10.02</td>
<td>4.10</td>
<td>0.99</td>
</tr>
<tr>
<td>5 a</td>
<td>3.05</td>
<td>7.17</td>
<td>18.99</td>
<td>25.21</td>
</tr>
<tr>
<td>b</td>
<td>17.18</td>
<td>19.24</td>
<td>25.16</td>
<td>28.27</td>
</tr>
<tr>
<td>c</td>
<td>14.13</td>
<td>12.08</td>
<td>6.16</td>
<td>3.05</td>
</tr>
<tr>
<td>2 a</td>
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<td>c</td>
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<tr>
<td>c</td>
<td>23.16</td>
<td>21.10</td>
<td>15.18</td>
<td>12.08</td>
</tr>
</tbody>
</table>

**Diagram:**

- **Diagram 1:** Two circles with distance (b) and (c) between them.
- **Diagram 2:** A circle with a line (b) and a distance (c) from the center.
CONCLUSIONS

Motion seems to affect accuracy more than the position of the button, but the middle position can be used to best reduce the effects of motion and to reduce the amount of variability in a person's pushing accuracy. Therefore, if accuracy, size and spacing are the major considerations it is recommended to place devices with push buttons in the middle position (this may not be recommended if the buttons must be used often, since a higher mounting position would not require the driver to look as far down into the car and away from the road). This study has shown that circular pushbuttons will provide a nearly optimal design in terms of performance and space utilization requirements for the conditions investigated. The use of mostly square buttons by today's designers is assumed to be mainly due to esthetic considerations rather than functional considerations inspite of the fact that such designs may result in lower pushing performance or use up too much valuable space. Far too many push button guidelines give a specified dead space between push buttons regardless of their size. This is conceptually wrong because the required dead space is directly related to the push button size. For example, larger push buttons require less dead space than smaller buttons to achieve the same confidence level that the operator will not inadvertently hit any adjacent buttons. Also, these guidelines generally do not take into consideration the need to design push button arrangements for different levels of hit and inadvertent hit confidence levels. As part of this study, a PC program was developed that makes use of the cumulative curves (see Figure 16) which are stored in a FoxPro data base program. This program is user-friendly and provides a designer with instantaneous push button size and spacing dimensions for a given set of input specifications and is also useful in the evaluation of existing push button designs.

The experimental portion of this study was fairly limited in the number of factors, the number of levels of each factor and the populations which could be investigated. Such as, only using one vehicle on a single road surface. With a limited number of speeds and with a fairly limited population. However, the real value of this study lies in its approach to gathering the data, converting the data into cumulative hit probability curves and the techniques used to convert these cumulative hit curves into push button size, spacing and clearance requirements for desired confidence levels that take into consideration an adjustment procedure for varying finger-tip widths.
and varying amounts of the finger-tip width being required to activate a push button. The proposed push button design methodology appears to be sound and with the development of a more elaborate data base as well as the addition of a graphics output option to the PC program, it will be able to provide designers with a design and evaluation tool for push button arrangements. By incorporating desired confidence levels for hitting a push button and not hitting adjacent push buttons, this tool will be able to assist in designing a push button arrangement with the required performance characteristics while requiring the minimum amount of space.

REFERENCES


