Proceedings of STRATEGIC HIGHWAY RESEARCH PROGRAM AND TRAFFIC SAFETY ON TWO CONTINENTS in Gothenburg, Sweden, 27-29 September, 1989

- Work Zone Safety
- Heavy Truck Safety
- Highway Safety
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- Work Zone Safety
- Heavy Truck Safety
- Highway Safety
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.

Under development for 2-3 years, 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 1989

Kenneth Asp

Proceedings of STRATEGIC HIGHWAY RESEARCH PROGRAM AND TRAFFIC SAFETY ON TWO CONTINENTS in Gothenburg, Sweden, 27-29 September 1989:

VTI RAPPORT 349A
- Opening
- International Harmonization of Test Procedures and Requirements for Roadside Safety Features, Workshop

VTI RAPPORT 350A
- Asphalt
- Long Term Pavement Performance

VTI RAPPORT 351A
- Work Zone Safety
- Heavy Truck Safety
- Highway Safety

VTI RAPPORT 352A
- Highway Operations
- Concrete and Structures
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**WORK ZONE SAFETY**

**Work Zone Safety**
Rudolph M Umbs, Federal Highway Administration, USA

**Analysis of Driver Behaviour and Accidents at Work Sites on German Motorways**
Wilhelm Kockelke, Bundesanstalt für Strassenwesen (BASt), Federal Republic of Germany

**Coordinated Approach to Traffic Control Management through Multiple Highway Construction Contracts**
Hermann A Guenther, Daniel, Mann, Johnson & Mendenhall (DMJM), USA

**Safety at Roadworks**
Michael Marlow, Transport and Road Research Laboratory (TRRL), United Kingdom

**Warning Lights on Service Vehicles in Work Zones**
Richard F Pain, Transportation Research Board (TRB) and Fred N Hanscom, Transportation Research Corporation, USA
HEAVY TRUCK SAFETY

Analysis of Statistical Data on HFV-Accidents and Vehicle Measures to Improve Safety
Ulrich W Stöcker, Bundesanstalt für Strassenwesen (BASt), Federal Republic of Germany

Vehicle and Driver Factors in Relation to Crash Involvement of Heavy Trucks
Ian S Jones, Forensic Technologies International Corporation, and Howard S Stein, Callow Associates, USA

Evaluation of Handling and Braking Characteristics of Heavy Vehicles
Andreas Schindler and Klaus Rompe, TÜV Rheinland, Federal Republic of Germany

Heavy Vehicle Braking - U S vs Europe
Richard W Radlinski, Vehicle Research and Test Center (NHTSA), USA

Braking Safety of Heavy Vehicle Combinations in the Nordic Countries
Lennart Strandberg, VTI, Sweden

Safety Aspects of Heavy Goods Vehicle Design
P H Bly and B S Riley, Transport and Road Research Laboratory (TRRL), United Kingdom

HIGHWAY SAFETY

Advantages of a Comprehensive Risk Analysis in Road Engineering
Walter Durth, Technical University of Darmstadt, Federal Republic of Germany
New Method for Accident Analysis
Olga J Pendleton, Texas Transportation Institute and Carl N Morris, University of Texas, USA

Evaluation and Comparison of Traffic Safety on High Standard Rural Roads
Ulrich Brannolte, Karlsruhe University, Federal Republic of Germany

Road Design and Safety
Karl-Olov Hedman, VTI, Sweden

Future Highway Safety Program
Jerry A Reagan, Turner Fairbank Highway Research Center, USA
Papers presented at the seminar were as follows: Work Zone Safety (Umbs, R M); Analysis of Driver Behaviour and Accidents at Work Sites on German Motorways (Kockelke, W); Coordinated Approach to Traffic Control Management through Multiple Highway Construction Contracts (Guenther, H A); Safety at Roadworks (Marlow, M); Warning Lights on Service Vehicles in Work Zones (Pain, R F and Hanscom, F N); Analysis of Statistical Data on HFV-Accidents and Vehicle Measures to Improve Safety (Stöcker, U W); Vehicle and Driver Factors in Relation to Crash Involvement of Heavy Trucks (Jones, I S and Stein, H S); Evaluation of Handling and Braking Characteristics of Heavy Vehicles (Schindler, A and Rompe, K); Heavy Vehicle Braking - US vs Europe (Radlinski, R W); Braking Safety of Heavy Vehicle Combinations in the Nordic Countries (Strandberg, L); Safety Aspects of Heavy Goods Vehicle Design (Bly, P H and Riley, B S); Advantages of a Comprehensive Risk Analysis in Road Engineering (Durth, W); New Method for Accident Analysis (Pendleton, O J and Morris, C N); Evaluation and Comparison of Traffic Safety on High Standard Rural Roads (Brannolte, U); Road Design and Safety (Hedman, K-O); Future Highway Safety Program (Reagan, J A).
WEDNESDAY SEPTEMBER 27

OPENING

9.00 - 11.30

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

Opening Speeches
Mr Åke Norling, County Governor, Gothenburg, Sweden

Mr Thomas B Deen, Executive Director, Transportation Research Board (TRB), USA
Mrs Monica Sundström, Director General, Swedish Road and Traffic Research Institute (VTI), Sweden

Overview of Traffic Safety in the United States
Mr Marshall Jacks Jr (Mr R Clarke Bennett, Director, Office of Highway Safety (FHWA), USA)

European Trends in Road Safety Research
Mr David Cornelius, Executive Director, Transport and Road Research Laboratory (TRRL), United Kingdom

Highways for the Future: The Strategic Highway Research Program (SHRP)
Dr Damian J Kulash, Executive Director, Strategic Highway Research Program, USA

Need for Road Maintenance Research in the Nordic Countries
Mr Tord Lindahl, Research director, VTI, Sweden
INTERNATIONAL HARMONIZATION OF TEST PROCEDURES AND REQUIREMENTS FOR ROADSIDE SAFETY FEATURES, WORKSHOP

11.30 - 17.00

Chairman: Mr Thomas Turbell, VTI, Sweden

Status Reports on Current Regulations
Australia Mr Rod Troutbeck, ARRB
Canada Mr Randy Sanderson, Transport Canada
Mr Frank DeVisser, Ministry of Transport
France Mr Robert Quincy, INRETS
Italy Mr Francesco La Camera, La Sapienza
Mr Pasquale Colonna (written presentation only)
Netherlands Mr Tom Heijer, SWOV (including presentation of VEDYAC)
Sweden Mr Thomas Turbell, VTI
United States Mr Jarvis Michie, Dynatech

12.30 LUNCHEON

14.00

NCHRP Report 230 Update
Dr Hayes Ross, Texas Transportation Institute (TTI), USA

Current Issues in Work Zone Safety
Mr William Hunter, Highway Safety Research (HSRC), USA

Harmonization Within the European Common Market
Mr Thomas Turbell, VTI, Sweden

Manufacturers Views on Harmonization
Mr Hans Norin, Volvo Car Corporation, Sweden
Mr Mike Dreznes, Energy Absorption Systems, USA

Panel Discussion
Subjects:
Requirements, Severity Index
Flail space, Theoretical Head Impact Velocity
Belted car occupants
Side impacts

Introduction by: Mr Gordon Bacon, MIRA

Introduction by: Mr William Hunter, HSRC
Introduction by: Mr Malcolm Ray, Vanderbilt University

Summary
Mr Thomas Turbell, VTI, Sweden
WEDNESDAY SEPTEMBER 27

ASPHALT

11.30 - 17.00

Chairman: Mr Bo Liljedahl, The Swedish Asphalt Pavement Association, Sweden

SHRP's Asphalt Research: Progress and Products
Dr Edward T Harrigan, Strategic Highway Research Program, USA

Asphalt Research in the Finnish ASTO-project
Dr Asko Saarela, Technical Research Centre, Finland

Data Distributions for Asphalt Concrete Resilient Modulus and Indirect Modulus
Ms Mary Stroup-Gardiner (Prof David Newcomb, University of Minnesota, USA)

Bitumen and Asphalt Mixes in USA, how do they look like?
Mr Andre Gastmans, Nynas NV, Belgium

What can Europe Learn from SHRP Asphalt Research?
Panel discussion

THURSDAY SEPTEMBER 28

WORK ZONE SAFETY

9.30 - 13.00

Chairman: Mr R Clarke Bennett, Director, Office of Highway Safety (FHWA), USA

Work Zone Safety
Mr Rudolph M Umbs, Federal Highway Administration, USA (Mr R Clarke Bennett)

Analysis of Driver Behaviour and Accidents at Work Sites on German Motorways
Priv Doz Dr-Ing Wilhelm Kockelke, Bundesanstalt für Strassenwesen (BASt), Federal Republic of Germany

A Coordinated Approach to Traffic Control Management Through Multiple Highway Construction Contracts
Mr Hermann Guenther, Project manager, Daniel, Mann, Johnson and Mendenhall, USA

Safety at Roadworks
Mr Michael Marlow, Transport and Road Research Laboratory (TRRL), United Kingdom

Service Vehicle Warning Light Systems for Work Zones
Dr Richard F Pain, Transportation Research Board, USA

VTI RAPPORT 351A
THURSDAY SEPTEMBER 28

HEAVY TRUCK SAFETY

14.00 - 17.30

Chairman: Mr Robert E Spicher, Director, Technical Activities, TRB, USA

Analysis of Statistical Data on HFV-Accidents and Vehicle Measures to Improve Safety
Dr-Ing Ulrich Stöcker, Bundesanstalt für Strassenwesen (BASt), Federal Republic of Germany

Vehicle and Driver Factors in Relation to Crash Involvement of Heavy Trucks
Dr Ian Jones, Forensic Technologies International, USA

Evaluation of Handling and Braking Characteristics of Heavy Vehicles
Prof Dr-Ing Klaus Rompe, Director, and Dipl.-Ing. Andreas Schindler, TÜV, Federal Republic of Germany

Heavy Vehicle Braking Characteristics - US and Europe
Mr Richard W Radlinski, Vehicle Research and Test Center (NHTSA), USA
(Mr Robert E Spicher)

Braking Safety of Heavy Vehicle Combinations in the Nordic Countries
Prof Lennart Strandberg, VTI, Sweden

Safety Aspects of Heavy Goods Vehicle Design
Dr P H Bly, Transport and Road Research Laboratory (TRRL), United Kingdom

VTI RAPPORT 351A
THURSDAY SEPTEMBER 28

LONG TERM PAVEMENT PERFORMANCE

9.30 - 17.30

Chairman: Dir Ivar Schacke, Head of the Danish Road Research Laboratory, Denmark

Long Term Pavement Performance: Progress and Products
Mr Neil F Hawks, Strategic Highway Research Program, USA
(Dr W R Hudson, Texas Research & Development Foundation)

Performance Monitoring and Data Acquisition for Pavement Performance Evaluation
Ms Cheryl A Richter, Strategic Highway Research Program, USA

Trends in Pavement Performance Based on the National Road Maintenance Condition Survey
Mr Peter Scott, Department of Transportation, United Kingdom

Canadian Long Term Pavement Performance Study: Recent Developments
Mr Greg Williams, Roads and Transportation Association of Canada, Canada

13.00 Luncheon

14.00

Future Pavement Performance Research Data Needs for Texas
Mr James L Brown, Texas Department of Highways and Public Transportation, USA

Means of Creating Links between US LTPP and European Monitoring Programs
Panel discussion

HIGHWAY OPERATIONS

15.00 - 17.30

Chairman: Mr Bo Simonsson, Swedish Road and Traffic Research Institute (VTI), Sweden

An overview of SHRP’s Highway Operations Research
Mr Don M Harriott, Strategic Highway Research Program, USA

Evaluation of Effectiveness of Pavements’ Preventive Maintenance Treatments
Dr Roger E Smith, Texas A & M University, USA (Mr Don Harriott)

ERASME – French Expert System for Pavement Maintenance
Mr Pierre Joubert, SETRA, France

Use of Rubber Modified Asphalt for Snow and Ice Control
Mr Hossein B Takallou, CTAK Associates, USA

VTI RAPPORT 351A
FRIDAY SEPTEMBER 29

HIGHWAY SAFETY

8.30 - 12.30

Chairman: Prof Kåre Rumar, Swedish Road and Traffic Research Institute (VTI), Sweden

Risk Analyses in Highway Engineering
Prof Dr-Ing Walter Durth, Techn University of Darmstadt, Federal Republic of Germany

New Methods for Evaluating Safety Measures Using Accident Data
Dr Olga J Pendleton, Texas Transportation Institute, USA

Evaluation and Comparison of Traffic Safety on High Standard Rural Roads
Dr-Ing Ulrich Brannolte, University of Karlsruhe, Federal Republic of Germany

Road Design and Safety
Dr Karl-Olov Hedman, VTI, Sweden

A Strategic Transportation Research Study for Highway Safety
Mr Jerry A Reagan, Turner Fairbank Highway Research Center (FHWA), USA
(Mr R Clarke Bennett)

CONCRETE AND STRUCTURES

8.30 - 12.30

Chairman: Dr Damian J Kulash, Strategic Highway Research Program, USA

SHRP’s Concrete and Structures Research: Goals and Recent Developments
Dr Damian J Kulash, Strategic Highway Research Program, USA

Concrete Microstructure Research and Its Applications in Highway Pavements
Dr G M Idorn, G M Idorn Consult, Denmark

Chloride Removal and Corrosion Protection of Reinforced Concrete
Mr John Miller, N O T, Norway

Chloride Binding in Cement and the CL/OH-Ratio of the Pore Solution
Univ Doz Dr Josef Tritthart, Graz University of Technology, Austria

Corrosion Protection of Reinforcement Against Chloride Impact
Univ Doz Dipl-Ing Dr Gerhard Hartl, Austrian Concrete Research Institute, Austria

Protecting Concrete by Flexible Waterproofing Slurries
Dipl Ing Andreas Volkwein, Technical University of Munich, Federal Republic of Germany
Participants in international conference in Gothenburg 27-29 SEPT 1989
"Strategic Highway Research Program and Traffic Safety on Two Continents"

Al-Dhalaan Mohamed
Andersson Olle
Andersson Ingmar
Antilla Osmo
Asp Kenneth
Augustin Harald
Bacon Gordon
Beck D L
Bennett R Clarke
Berglund Liliane
Bertilsson Häkan
Bjelkengren Stig
Bladlund Anita
Bly Philip H
Borsje Johan
Brandberg Valter
Brannolte Ulrich
Braunovic Predrag J
Breyer Quenter
Brown James L
Calvet Pere
Cannell Alan
Carlsson Hans
Carlsson Gunnar
Chinsen Dat
Clarke David B
Colonna Pasquale
Cornelius David
Deen Thomas B
DeVisser Frank
Dirmböck Gunther
Dreznes Michael G
Durth Walter
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Ehn Lars
Ekholm Leif
Eklund Jan
Engervall Dag
Eriksson Häkan
Eriksson Ing-Marie
Fredriksson Rune
Fältner Leif
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Gloersen Per G
Gorle Dirk
Gray John
Guenter Hermann A
Gyllensten Siv
Gynnerstedt Gösta
Harrigan Edward T
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Hartl Gerhard
Hedean Karl-Olov
Heijer Tom
Helgason Jon
Herbst Gerhard
Hortlund Kjell
Hunter W R
Hunter William
Hurley Barry
Höbeda Peet

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Royal Inst of Technology
Skanska AB
Roads and Waterways Adm
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BFVA ARSENAL
M I R A
International Bitumen Emulsions Corp
VTI
Swedish Road Administration
Swedish Asphalt Pavement Ass
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T R R L
Delft University of Technology
Kommunförbundet
University of Karlsruhe
The Highway Institute
Federal Highway Administration
Texas State Department
Institut Catala Desenvol Transp
Volvo Do Brasil
Sabena Material AB
VTI
SweRoad
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Amt der Steiermärkischen Landesregierung
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Technische Hochschule Darmstadt
Energy Absorption System Inc
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Central Road Testing Lab
Nynäs Petroleum AB
Texas Res and Dev Foundation
BP Chemicals
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AUSTRIA
USA
UNITED KINGDOM
SWEDEN
Participants in international conference in Gothenburg 27—29 SEPT 1989
"Strategic Highway Research Program and Traffic Safety on Two Continents"

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Jansson Birgitta VTI SWEDEN
Jones Ian S Forensic Techn International USA

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Jämsä Heikki V T T FINLAND
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<tr>
<th>Name</th>
<th>Institution</th>
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<tr>
<td>Ray</td>
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<td>Reinestam</td>
<td>Göran Swedish Road Safety Office</td>
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Work Zone Safety

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WORK ZONE SAFETY
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ABSTRACT

A Nation's highway system is critical to its economic well-being. Over the years, these systems have served their purpose. But now many highways are wearing out and in need of major repair work. Unfortunately, this work often must be done next to high speed, high volume traffic. This work reduces capacity causing traffic congestion, increases danger to the motorists and workers and increases work and motorists' costs and delay.

To minimize the problems created by the work, Europe and the USA are developing active programs and innovative approaches to provide effective and safe traffic control and worker protection. This paper will discuss the similarities and differences between the European countries and the USA in the following areas.

-- Accident experience: location, type, number and severity;
-- Data bases and methods of assessing traffic flow and costs;
-- Traffic management strategies: planning, public awareness campaigns, scheduling, implementation, and inspection,
-- Traffic management techniques: lane closures, diversions and one-way operations; and,
-- Traffic control devices: signing, signaling, markings, channelization and barriers.
Introduction

Road maintenance and reconstruction are necessary and continuing activities for all road authorities. On both continents, the road systems are aging, traffic volumes are increasing, and the number and weight of trucks are increasing. These are causing major reconstruction needs. This work is taking place on the existing busy roadways, next to high speed, high volume traffic. Working next to traffic increases hazards to workers and motorists, creates traffic congestion, and increases works' and motorists' costs. The impact on safety of this road work is quite apparent. For example in the United States, the number of work zone fatalities rose 44 percent from 489 in 1982 to 703 in 1984. This increase coincided with a major increase in road work on the existing freeway system and other major roads. Over the last 4 years work zone fatalities have stabilized at about 700 per year. On the U.S. freeway and major road systems, an estimated 46,000 work zones accidents are occurring annually. Of these, about 400 are fatal accidents resulting in almost 500 fatalities, 15,000 are non-fatal accidents and 31,000 are property damage only accidents.

Accident experience

On both continents, most countries collect and analyze only limited work zone accident data. As a result, it is difficult to assess the size of the safety problem. Also because each country uses different criteria and analysis techniques, the results from the individual countries cannot be easily compared. However, based on the data available, the general anatomy of the work area accident problem on both continents appears to be similar.

- The rate of personal injury accidents (per million vehicle km) in a work zone is higher than on the same road without a work zone.

- The accident rate is not uniform throughout the work zone. This depends on the length, geometry, type of work and strategy such as contra-flow operation or lane closure.

- The weekend and holiday accident rates in work zones are higher than during the week.

- For short term work activities, the accident rate is above non-work zone especially during the peak periods.

An analysis of work zone accident data in the U.S. found:

- The freeway system accounts for about 30 percent of all work zone fatalities compared to 10 percent of all fatalities.
- The truck fatality involvement rate in work zones is twice that in non-work zones.
- Urban work zones have 66 percent of the injuries and 71 percent of all work zone accidents, mainly vehicles striking other vehicles during the daytime.
- Rural work zones accidents than urban. Rural accidents account for 64 percent of all work zone fatalities, often single vehicles hitting fixed objects at night.
- While less than 30 percent of all work zone accidents occur at night, they account for almost 50 percent of the fatalities.

Therefore we are placing special emphasis on freeway work zones, nighttime guidance, and smoother daytime traffic flow.

Data bases and methods of assessing traffic flow and costs

Traffic information used in planning, scheduling, and designing work zone traffic controls and strategies is very important. Most countries are now developing road data bases as part of their overall plan for managing their road system. While the data varies between countries, the commonly collected data are traffic volumes, accidents and road and bridge condition.

The total cost of road work consists of two parts: costs of the work and the user costs. The work costs include the materials, labor and traffic controls. The user costs are less precise. These costs consists of many parts, such as, delays, vehicle operation and accidents. They vary by country depending on the assumptions made and values used. When assessing the total costs of the work, many countries consider both costs. High user costs may dictate changes in the design, scheduling, traffic control, construction procedures and materials.

Several countries have developed economic models to determine the impact of the projects on safety and operations and the social, economical and environmental costs. For example the United Kingdom uses two computer programs: COBA9 (COst Benefit Analysis) and QUADRO2 (QUeues And Delays at ROadworks). The COBA9 is concerned with identification, evaluation and comparison of the costs and benefits of new traffic strategies during a given period. The second program, QUADRO2, provides a method of economic assessment of road maintenance.

In the U.S., five categories of analysis tools are being used to determine the potential impact of major projects. These are network-based highway and transit planning models, quick-response estimation techniques, highway capacity analysis procedures, traffic simulation models and traffic optimization models.
Traffic management strategies

To meet the increasing demands of the road system, traffic management strategies are being used. The strategies provide a balance between safe and efficient operations for the contractor and safe and efficient travel for the motorists.

These strategies involve:
- Placement and timing of work zones,
- Planning and implementing the construction work
- Financing the work
- Motorists' needs and behavior

Many countries are using the following measures in the development of the strategies:
- Shortening the construction time, especially on roadways with high volumes,
- Better coordination and timing of adjacent projects, thus avoiding a concentration of work zones along a transportation corridor.
- Reducing the number of work zones during peak period such as on holidays and commuter rush hours.
- Public awareness campaigns that inform and warn the motorists of the hazards of work zones and the need for caution.

Many motorists do not appear to fully appreciate the hazards and the need for caution at work zones. In recognition of this problem, several countries have started programs to increase the motorists' awareness. A principal focus of these programs is to advise motorists of the dangers workers experience working close to fast-moving vehicles and the need for motorists to reduce their speed and use extra care at the work zone.

In the U.S., the State of California conducted the first major statewide public awareness program. California adopted the slogan "California Highway Workers --Give 'em a BRAKE," as the central theme of its program. Other States are now conducting similar programs. All of the programs provide motorists with a better appreciation of work zone hazards. The programs have improved roadway worker morale through positive action by management to make the work zone safer.

Public information programs are also being used on a project basis to inform the public, businesses and media of potential disruptions to normal activities and steps being taken to minimize the disruption. The purpose of these programs is to describe the reasons for the work; alleviate fears; and provide information such as alternate routes and modes of transportation, road closures and construction times.

In the U.S., we have found that effective public information programs are essential to successful projects. Also these
programs result in good public relations and political support for future projects.

In Germany, route related plans are analyzed to determine if the disruptions will be acceptable. The press receives a map of the road network showing the locations of projects. This is done to inform the public of possible delays and gives them an opportunity to choose alternate routes. The Dutch Road Association together with other parties started a special public relation and advertising campaign for mutual understanding between workers and motorists. Similar campaigns are being conducted in other countries.

Beyond the national scope at the European level, annual co-ordination talks are conducted each Spring within the framework of an international working group. On both continents, road work information is being provided the public through the media - newspaper, brochure, mailings, radio and TV.

Both continents use a traffic control plan (traffic signal plan in Europe) for most work zones to assure the safety of motorists, pedestrians and workers. The plan shows the sequencing of the work, placement and type of traffic control devices, and the strategies. Traffic control plans range in scope from a very detailed plan designed for a specific site, to simply a reference to the standard plans. They are designed to provide clear guidance to motorists and reduced exposure time of workers and motorists to work zone hazards.

To insure appropriate and properly maintained traffic control devices, most countries use a unit price method of payment for the installation, replacement, maintenance and cleaning. This method also allows for quick and efficient traffic control plan modification where necessary. However, on smaller projects a lump sum method of payment is often used.

To achieve the objectives of safe and efficient traffic flow and work activities, the planning, scheduling and design must be followed by proper installation and inspection. Installation and inspection are the responsibility of either the police, contractor, the highway authority or a combination.

Two methods of installing and removing traffic control devices are used. One method is for the road authority or police to install and remove the devices with the contractor maintaining the devices during the work. Another method is for the contractor or a firm specializing in traffic controls to be totally responsible for installation, maintenance and removal. Whatever method is used, the lines of responsibility must be clearly defined and understood by all parties. Inspection of the traffic control devices is generally done by the highway authority or police. They must insure that the traffic control
plan is operating as intended and the traffic control devices are properly maintained.

The training of responsible personnel is provided by the highway authority or the contractor. Only personnel with proper training and an understanding of the traffic control principles are normally responsible for work zone traffic control. In the U.S., a number of training courses are conducted by the Federal and State governments and private associations. Several States require that all of their supervisory personnel responsible for traffic control attend training courses and pass an examination.

Traffic management techniques

The traffic management techniques being used on both continents are quite similar. The names of the techniques may vary but the concepts are the same.

The diversion of traffic from the roadway with the work to another roadway may be the safest for the work activities. However, it is seldom acceptable because of the inconvenience to the motorists and those along the diversion roadway. Instead, contra-flow operations are commonly being used on both continents. The length of the contra-flow lanes varies by country from 6 km. to 24 km. The devices and spacing to separate opposing traffic also vary from markings and cones at 0.5 m spacing to portable concrete barriers continuously connected.

Controlling the speed of the vehicles through work zones is a common problem. Several methods are being used: regulatory signing, reduced lane width, barriers, gates, and police officers and cars. In the U.S., we found stationary police cars with radar to be the most effective method to control speeds.

Narrowing of lanes is being used to increase the work area while maintaining the same number of lanes. The minimum lane width varies by country, percent of trucks, and length of the narrowed lane from 2.5 m to 3.5 m.

Shuttle operations are used on a two-way, two-lane highway with low traffic volumes when work activities occupy one of the two lanes and continuous two-way traffic cannot be maintained. Three methods of single lane shuttle operations are being used on both continents: fixed priority using signing, hand-operated "Stop" and "Go" signs, and traffic signal control.

Traffic control devices

The purpose of traffic control devices is to insure the safe and efficient movement of all traffic throughout a highway system.
The basic guidelines and standards which govern the design and use of traffic control devices have been established by each country's highway authority.

In the U.S., national standards and guidance for providing traffic controls are stated in the "Manual of Uniform Traffic Control Devices" (MUTCD) and the "Traffic Control Devices Handbook." Our national Manual sets forth basic principles and standards for the design, application and installations of traffic control devices, including those for work zones. The Handbook is an operational guide to the Manual. It explains how to apply the Manual's standards.

The primary traffic control devices being used are signs, channelizing devices and pavement markings. Devices used at night are either retroreflectors or illuminated. Because of rough handling, work zone traffic control devices are normally durable and of high quality.

Some basic differences exist between the devices used on each continent. In Europe, the color scheme is red/white and blue/white. In the U.S., orange/white and orange/black are used. The sign shapes are also different. The regulatory signs are red circles in Europe and rectangular in the U.S. The warning signs are triangle in Europe and diamond shape in the U.S. The same type of channelizing devices are used on both continents - cones, cylinders and marker posts. However, in Europe these devices are more closely spaced than in the U.S. Also in the U.S., plastic barrels instead of steel barrels are commonly used. Many European countries use a different color pavement marking, such as orange in work zones. In the U.S., the same color markings are used on all roads. A common problem on both continents is the removal of inappropriate markings in work zones. The old markings often are not properly removed and new markings placed before the traffic patterns are changed.

Several innovative types of equipment and devices are being used to improve safety and efficiency. On both continents:

Arrow panels provide advance warning to the motorists to change lanes as indicated by the arrow. Such panels consist of a matrix of lights capable of displaying an illuminated flashing arrow. These panels are mounted either on stationary trailers or on the back of moving work vehicles.

Variable message signs are trailer or gantry mounted signs. These signs display real-time information on closed lanes, routing, speed advisories or unexpected queuing.

Proper worker clothing is being used to improve the chances of the workers being seen by the motorists. This clothing
has highly visible colors during the day and retroreflective markings at night.

In the U.S.:
Portable concrete safety shape barriers protect workers and motorists. The barriers prevent errant vehicles from entering the work site and redirect impacting vehicle with a minimum of damage to the vehicle and its occupants.

Attenuators or crash cushions, mounted on the rear of a truck, shield work vehicles and protect workers. Truck-mounted attenuators are made of a crushable material which absorbs the force of an impacting vehicle.

Conclusion

In the U.S., as a result of the programs and innovative approaches, improvements in work zone traffic safety are being made. There are new and expanding programs, improved traffic management and traffic control, and a stabilizing or decrease in work zone accidents. During the last 4 years, the work zone fatalities per billion dollars of construction expenditures has decreased 30 percent.

We believe that efficient work zone management can have a double pay-off. Besides increasing safety, highway authorities can foster good will with the public. Work zones represent one of the few direct opportunities for contact between the highway authority and the public. As a result, the public often judges the authority's competence on how well it operates work zones. Thus, good work zones are a "win-win" situation. They enhance safety and provide a good public image. What more can a public road official ask.
Analysis of Driver Behaviour and Accidents at Work Sites on German Motorways

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Analysis of driver behavior and accidents at work sites on German motorways

Work sites are critical sections in road networks and make high demands on driver's attention and adjustment. To guarantee safe and frictionless traffic flow, traffic control and signposting at work sites, especially on autobahns with high volumes, are very important factors.

This contribution describes a research project of the Federal Highway Research Institute, in which driver and speed behaviors were studied while passing work sites on German autobahns. One aim of the project was the analysis of the influence of signposting on speed, deceleration and following distance. Driving tests with an instrumented car, interviews of drivers and an analysis of accidents were conducted. The method and the results of these empirical studies are explained. Further items are the accident rates at particular sections of the work sites and the evaluation of the signing system.
ANALYSIS OF DRIVER BEHAVIOUR AND ACCIDENTS AT WORK SITES ON GERMAN MOTORWAYS
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Priv. Doz. Dr.-ING.
Federal Highway Research Institute

1. INTRODUCTION

Work sites on motorways are problematic both for organizers and drivers. Motorway sections involving road works make higher demands on vehicle drivers than do "normal" sections. When passing a work site, drivers have to fulfil various driving tasks, including in particular observing speed restrictions, keeping a safe distance to other vehicles, observing the flow markings and watching works traffic and oncoming vehicles. At the same time we note a generally higher rate of accidents at work sites compared to open sections of motorways in Germany [1]. About 6 to 8% of the total number of motorway accident fatalities occur at work sites. For this reason, greater attention is being paid to road safety at motorway work sites, particularly since the number of such sites will increase in the future [2].

A fundamental problem affecting safety at work sites is driver observance of an appropriate speed, indicated by signposting. As experience has shown in the Federal Republic of Germany, drivers exceed the speed limit frequently [1].

Information about driving behaviour at work sites is still relatively scarce. To estimate the influence of signposting in spatial terms, a rather more "long-distance" analysis of driver behaviour would be useful. This type of research requires the carrying out of test or trailing drives in real-life traffic, thus involving a quite considerable degree of work. Such a project has been carried out by the Federal Highway Research Institute (BASt). The following report describes the results of this study [3].

2. METHOD OF INVESTIGATION

The aim of the project was to investigate the passage of individual cars through the work site, and to identify possible variables influencing driving behaviour. The method chosen required drivers to negotiate a lengthy section of motorway featuring work sites in a vehicle equipped with measurement instrumentation. The object of the investigation was kept secret to ensure that driver behaviour was not influenced in any way. 22 participants of different ages were used in the trial, all exhibiting thoroughly
"normal" driving behaviour. During the drive, traffic in front and to the rear was recorded on video, and the measurement variables of speed, brake pedal and accelerator actuation, steering angle, time and distance were registered [4].

The drives took place during the day at average traffic volumes. The drive was around 180 km long. At the end of each drive, participants were questioned with a view to identifying attitudes and factors relevant to behaviour. These empirical results were complemented by accident analysis of the work sites passed through.

A total of 7 work sites with different traffic guidance systems were included in the investigation. Fig. 1 shows the major characteristics.

| U.d. Nr | Baustelle | Ortung | Typ | Verkehrs- | Fahr-/Verkehrs- | DTV | Geschwindigkeits- | Länge der Baustelle (m) | Länge des Verkehrs- | Art der Verkehrs- | Beschichtung (Regel-) |
|--------|-----------|--------|-----|Längenbereich|zahl|bereich |(m) |messungsbereich |(m) |messungsbereich |plan |
| 1 | Siegburg A3 Richtung Frankfurt | 2 | 4 x 0 | 3 | 2 | 24.000 | keine | 3.580 | 1.070 | 2.50/ | Überverung nach links | 1/7 |
| 2 | Klingpforter A3 Richtung Frankfurt | 1 | 3 x 3 | 3 | 3 | 23.000 | keine | 3.917 | 1.690 | 3.00/ | leichte Verzögerung nach links | 1/5 |
| 3 | Siegburg A3 Richtung Köln | 2 | 4 x 0 | 3 | 2 | 24.000 | keine | 3.782 | 1.230 | 2.50/ | leichte Verzögerung nach links | 1/7 |
| 4 | Kallenberg A4 Richtung Aachen | 2 | 4 x 0 | 2 | 2 | 33.000 | 100 | 3.477 | 1.420 | 2.50/ | leichte Verzögerung nach links | 1/3 |
| 5 | Kerpen A4 Richtung Aachen | 2 | 2 x 2 | 2 | 2 | 25.000 | keine | 3.908 | 1.940 | 3.75/ | Überverung nach links | 1/2 |
| 6 | Kerpen A4 Richtung Köln | 2 | 2 x 2 | 2 | 2 | 24.000 | 100 | 4.192 | 1.990 | 3.50/ | leichte Verzögerung nach links | 1/4 |
| 7 | Kallenberg A4 Richtung Köln–Bödendorf | 2 | 4 x 0 | 3 | 2 | 32.000 | 100 | 3.875 | 1.400 | 2.50/ | Überverung nach links | 1/7 |

Fig. 1: Main characteristics of investigated work sites

The signposting used at the work sites essentially corresponded to the "Guidelines for securing work sites on roads" (RSA 1986) [5].

3. RESULTS

3.1 Speed patterns

The measurement results permit a detailed reconstruction of the progress of each drive. Fig. 2 shows the speeds travelled for two work sites. 3 areas
can be identified which display similar characteristics: the uninfluenced approach area (B1), the deceleration section (B2) and the inner work site area with lower speed level (B3). Vehicles approached the work sites at speeds averaging 110 to 130 km/h in a homogenous flow of traffic. Within the signposted approach areas, speed levels began to fall in the approximate area where signposting became more frequent, at around the 800-m danger sign, and the deceleration process was introduced. Overall, the phased reduction of the speed limit was only observed to a certain extent and with a certain delay; even the slowest travel speeds still almost always exceeded the maximum speed limit.

The incidence of speeding (Fig. 3) increased as the speed limit fell. Speed limits of 100 km/h were exceeded by an average of 9 km/h, limits of 80 km/h by an average of 22 km/h and limits of 60 km/h by an average of 30 km/h. Speed behaviour was only seen to level down in situations where additional local factors affected driving, i.e. crossover points. The lowest speeds were driven here, although still averaging between 65 and 85 km/h. Here, the range of different speeds was narrower. Speeds generally increased within the work sites, falling to another low level at the second crossover point; this level was still higher than that at the first crossover point, however.

Fig. 2: Example of speed progressions at 2 work sites (22 trial drives, work site 1 and 5)
Fig. 3: Mean values and standard deviations of speeds at speed limits

Speeds within the work sites rose by an average of 9 km/h compared to the speed at the first crossover point. Where the speed limit was 60 km/h, average values of between 71 and 81 km/h were recorded. Where the speed limit was 80 km/h, the mean values were 85 – 93 km/h. It was seen that the lowest speeds were travelled in work sites with direct oncoming traffic and narrow lanes.

3.2 Deceleration, gap acceptance, changing lanes

Fig. 4: Average decelerations and standard deviations in approach areas
Average deceleration in the signposted approach areas was relatively low. Deceleration averages ranged between 0.1 and 0.5 m/s² and did not appear to follow any law. Standard deviations were max. 0.4 m/s². This shows that deceleration at the work sites was more or less uniform. Deceleration behaviour can therefore be characterized overall as moderate (Fig. 4). Vehicle brakes were applied relatively seldom; speed reductions were generally achieved by the driver taking his foot off the accelerator or by his changing down a gear.

Distances between vehicles lessened during passage through the work sites, i.e. the stream of traffic grew more dense at work sites. However, no accumulations of dangerously short distances (less than 1 sec. to the car in front) were registered either during travel through work sites or before crossover points. Despite traffic lanes at times being considerably narrowed, there were only a few cases of road studs being crossed. The extent of lane reshaping also appeared to have no influence, and in the cases investigated it can therefore be said that the crossover points were constructed well and uncritically from the point of view of driving dynamics. During the trials there were nevertheless a few instances within crossover sections where - obviously unintentionally - drivers continued straight ahead and changed lanes. This may be an indication that the lane diversion was identified either incorrectly or too late. Drivers changed lane less frequently within the work site area itself than in the approach and deceleration areas. In narrow driving conditions, in particular in 4 + 0 layout systems, drivers tended to remain in the lane first chosen.

3.3. Attitudes to speed regulations

The following can be deduced from the interviews with the drivers:

- The motorway work sites were not considered to be unusual driving situations.

- The work sites were considered to be relatively dangerous in comparison to open road sections. Drivers experienced the greatest difficulties in narrowed sections and at crossover points, and "when lorries are around".

- Speed regulations were interpreted very loosely, i.e. the majority knew they were exceeding the...
speed limit. However, the signposting of the 60 km/h limit was thought to be necessary since it drew attention to the fact that a dangerous "crossover point" was coming up.

Most drivers thought the heavy signposting of work sites was necessary as a means of arousing and maintaining attention. Whether or not traffic regulations should be observed was variously interpreted, often depending predominantly on the situation.

3.4 Accident occurrence

In the accident investigation carried out at the same time as the test drives, 533 accidents were recorded. It was shown that the accident rate in the area of the work site had risen by some 40% compared to the period prior to road maintenance. The previous accident rate of 0.8 had risen to 1.15 [accidents/10^6 vehicle km]. The most dangerous section of the work sites were the first crossover points, followed by the inner work site areas, the approach sections and finally the second crossover points. The relatively short length of the crossover points must be taken into account when interpreting accident rates in these sections. In absolute terms, most accidents occurred in the signposted approach areas and within the work sites, while the crossover points were less significant in terms of absolute figures (Fig. 5).

The most frequent type of accident in the approach areas involved collisions with the vehicle in front (41%), while leaving the carriageway was most frequent in the crossover points (30%). In the inner areas, collisions with oncoming vehicles occurred relatively seldom (4%). The main cause of accidents in all areas was "unsuitable speed" (25%).

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<th>Work site section</th>
<th>Accident rate [A/10^6 veh/km]</th>
<th>Number of accidents</th>
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<tr>
<td>Approach area</td>
<td>1.08</td>
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<tr>
<td>1st crossover point</td>
<td>1.31</td>
<td>29</td>
</tr>
<tr>
<td>Inner area</td>
<td>1.20</td>
<td>108</td>
</tr>
<tr>
<td>2nd crossover point</td>
<td>0.81</td>
<td>19</td>
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Fig. 5: Accident numbers and accident rates at the 7 work sites (1987)
4. CONCLUSIONS

The aim of the study was to investigate speed behaviour at motorway work sites on the basis of test drives, and to identify relationships between driving behaviour, signposting and accident occurrence. The study covered 7 work sites, involved 22 trial participants and evaluated 533 accidents. We can draw the following conclusions:

The current form of signposting used on motorway work sites in the Federal Republic of Germany grants motorists a freedom in terms of speed and deceleration behaviour which appears to be necessary when differences in approach speeds and changes in traffic and weather conditions are taken into consideration. Sudden braking can clearly be avoided by the early announcement of work sites and prolonged speed funnels. From these points of view, a spatial concentration of deceleration processes would not appear advisable.

An unsatisfactory aspect of this concept, however, is undoubtedly the speeding which was observed in all areas of the work sites. In heavy traffic involving the possibility of traffic jams, this problem could gain even greater significance. The analysis of accident occurrence, which shows a clear increase in accident rate, confirms the risks involved. The hazards posed to work site operation should also be taken into consideration.

An urgent aim of improvement measures should therefore be the greater observance of the prescribed speed limit. Police surveillance can play a major role in this regard, particularly where speeding is deliberate. Whether visual measures, warning devices or stronger emphasis on the start of the work site and crossover points might prove effective needs to be tested in real life. The introduction on motorways of measures affecting driving dynamics is only possible to a limited extent.
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A Coordinated Approach to Traffic Control Management through Multiple Highway Construction Contracts

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A COORDINATED APPROACH TO TRAFFIC
CONTROL MANAGEMENT THROUGH MULTIPLE
HIGHWAY CONSTRUCTION CONTRACTS

ABSTRACT

When the Colorado Department of Highways (CDOH) implemented a revolutionary new traffic control management program to support the construction of I-70 through Glenwood Canyon, it knew that it had achieved a level of operational efficiency, safety and public acceptance that would not have been possible under any traditional approach. The project, located in the Rocky Mountains of Western Colorado, was faced with numerous constraints and delays due to complexity and controversy, not least of which was the problem of constructing the new four-lane divided highway in the exact location of the existing narrow two-lane roadway, while accommodating as many as 15,000 vehicles per day during peak periods.

The need for special traffic control considerations was recognized during the planning and early design stages, but no definitive steps to address this problem had been taken at the time construction began in 1981. As construction activities intensified, with each contractor conducting his own traffic control operations in the traditional manner, it became readily apparent that a total loss of control, with its inherent safety and operational implications, was imminent unless a completely different approach to traffic control was taken. This approach emerged from a comprehensive study, commissioned by CDOH and conducted by its management consultant, Daniel, Mann, Johnson, & Mendenhall (DMJM), which covered the principal factors of traffic operations and emergency procedures. The study proposed a traffic control management plan that included a pilot car operation; a sophisticated radio communications network; coordinated flagging operation; and an overall traffic control support contract that combines all traffic control elements under the authority of CDOH.

This rather radical departure from traditional methods was approved by the Federal Highway Administration (FHWA) and portions of it were placed into operation in April 1985. The remainder of the plan was implemented during the ensuing months and has been in effect ever since. In September 1986, the Institute of Transportation Engineers (ITE) recognized this unique program by bestowing upon CDOH and DMJM its annual Transportation Achievement Award for Operations.

This paper presents in detail a description of the program and how it differs from traditional traffic control methods; an analysis of the operational benefits that have accrued to contractors as well as motorists; the safety enhancements that have resulted in a dramatic reduction of accident rates; the management structure that makes this type of operation possible; and an analysis of the costs associated with this program. The paper also offers thoughts on the applicability of this type of program, or portions thereof, to other projects.
A COORDINATED APPROACH TO TRAFFIC CONTROL MANAGEMENT THROUGH
MULTIPLE HIGHWAY CONSTRUCTION CONTRACTS

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Affiliation: Daniel, Mann, Johnson, & Mendenhall (DMJM)

1. INTRODUCTION AND BACKGROUND

To support the construction of a segment of Interstate Highway in western Colorado, a unique and innovative traffic control management program was implemented. The program has proven highly successful in conducting the flow of traffic through extremely restricted construction work zones and has been acclaimed for the high level of efficiency and safety it affords both construction contractors and the traveling public. This departure from traditional traffic control methods has resulted in the emergence of an award-winning process that removed the final obstacle confronting the successful completion of this important highway project and has been the subject of numerous technical papers and presentations across the United States. This paper provides a complete description of the program along with an analysis of the principal factors of operations, safety and costs.

1.1 Interstate Highway System Definition

In 1956, the United States Congress enacted a law which provided for implementation of the largest public works program in modern history - the construction of the 43,000 mile (69,000 km) National System of Interstate and Defense Highways, better known as the Interstate Highway System. Its primary function was to provide safe, high capacity highways linking nearly all major population centers in the 48 contiguous states. Over 85% has been completed at a cost of $109 billion. The remaining 6,500 miles (10,400 km) necessary to complete the network, or to bring older sections up to standards, include some of the technically most difficult and consequently most expensive segments. Confined mainly to urban areas as well as difficult and environmentally sensitive terrain, these "vital gaps" as defined by Congress, are estimated to cost an additional $16 billion.

1.2 The Interstate System in Colorado

The State of Colorado was designated to receive 960 miles (1545 km) of Interstate Highway, which includes a major segment of one of the principal east-west routes across the United States, Interstate Highway 70 (I-70). I-70 enters the state from the great plains of the American mid-west, crosses the spine of the Rocky Mountains and then meanders across the high desert of the Colorado River plateau as it leaves the western boundary of the state. Enroute, I-70 passes through the busy Denver metropolitan area, then climbs 5,800 feet (1770 m) in a mere 50 miles (80 km) to the point where it crosses under the Continental Divide via the Eisenhower Memorial Tunnel, the highest vehicular tunnel in the world. At 11,112 feet (3388 m), this is the highest elevation reached on the entire Interstate System.
Within the next 100 miles (161 km), this magnificent highway traverses some of the most spectacular scenery in North America, including the 10,666 (3252 m) high Vail Pass. It then enters the spectacular gorge of the Colorado River known as the Glenwood Canyon. The decision to locate I-70 within this 12.5 miles (20 km) long canyon was the culmination of years of intense study which had been undertaken to relax the controversy and public outcry that arose when this natural phenomenon was first suggested as a possible corridor for I-70. It was that decision which gave the Colorado Department of Highways (CDOH) the unique opportunity to embark upon and complete one of the most challenging highway construction programs ever undertaken. The administrative and management techniques, specifically developed by CDOH, relating to traffic control and public safety, are the subject of this dissertation. Without these techniques, the construction of the divided four-lane highway under continuous traffic, and in compliance with Interstate Highway standards, would have been virtually impossible. Some specific background and explanation is necessary, however, before the traffic control management program discussed herein can be assessed from the proper perspective.

1.3 Project History and Design Development

Glenwood Canyon is a narrow gorge, up to 2,000 feet (610 m) deep, which was carved over eons by the waters of the Colorado River. It is not as large or as well known as its sister canyons further downstream in Utah and Arizona; it is, however, no less spectacular. The extremely narrow bottom of the canyon is mostly occupied by the river, yet it has served as a transportation corridor for over 100 years. At the base of the south canyon walls runs a mainline railroad track that was first built in 1887; a narrow paved two-lane highway has been in existence along the north side since the early 1930's, although primitive cart tracks had been carved out of the rock and talus before the turn of the century.

When all alternative routes for I-70 had been eliminated because of environmental, physical and economic obstacles, the only feasible and acceptable option was to construct the new four-lane highway in the exact location of the existing two-lane road. For years this established alignment has served as the major ground transportation route connecting Denver with the largest population centers in the west. The final approval to construct I-70 through Glenwood Canyon was encumbered by numerous public commitments and legal stipulations intended to mitigate the many concerns that were the subject of years of study, deliberation and court action. Among the conditions that had to be satisfied, it was mandated that the new highway must:

- Not damage the natural canyon environment.
- Accommodate and enhance the recreational opportunities that have prevailed along this reach of the Colorado River.
- Afford aesthetic appeal that will be compatible with the grandeur of the Canyon.
- Be constructed while maintaining the safe flow of traffic.

In meeting these and many other demands, a special Design Team, consisting of top designers and technicians from all over the United States, was established. The Design Team was charged with the responsibility to identify the constraints, formulate methods for mitigation, develop plans for implementation, and finally supervise the construction in order to ensure that all commitments will have been satisfied.
1.4 Mitigation Elements

Protection of the natural environment entailed provisions for constructing the new highway in a manner that would minimize disturbance of natural features such as land form and vegetation. In recognition of this requirement, the U.S. Congress, in its 1976 Federal Aid Highway Act, cited Glenwood Canyon as a unique project deserving special treatment. Accordingly, this law grants the project certain variances from Interstate Highway design standards in order that I-70 can better fit into the available space in the Canyon.

Furthermore, a subsequent Federal Aid Highway Act in 1981 authorized special construction features, not normally permitted, to be fully eligible for federal funding under the normal apportionment formula. This decision resulted in the inclusion of over 20 miles (32 km) of aesthetically designed retaining walls; 39 bridges and viaducts with a total length of over 6.5 miles (10.5 km); post-tensioned pavements, cantilevered beyond the face of the retaining walls by six feet (two meters); and twin tunnels that completely remove the highway from view in one of the most scenic recreational sections of the canyon.

Recreation activities in Glenwood Canyon have traditionally included river rafting, kayaking, fishing, hiking and sightseeing. As interpreted by the Federal Highway Administration (FHWA), the 1981 law stipulated that the Glenwood Canyon project would be eligible for Federal funding for such amenities as bicycle paths and rest areas, which were necessary components that would allow the project to conform to earlier commitments. These and many other special elements are being integrated into the project.

The need to maintain traffic throughout the construction period resulted in a sequencing and scheduling program that separated the project into 32 construction contracts requiring numerous detours and crossovers. Whenever possible, major elements such as retaining walls and bridge segments were designated to be prefabricated off-site, thus minimizing the logistical problems of materials storage and handling, as well as on-site fabrication, in such a limited space. Therefore, it was concluded during the early stages of design that the entire project could indeed be constructed while maintaining as much as 15,000 vehicles per day through intensely active work zones. What had not been determined was how this traffic was to be managed once it got into these construction zones.

2. THE PROBLEM

2.1 Commitment to Construct Under Traffic

Once the decision to build I-70 through Glenwood Canyon had been made, it was understood that construction could be accomplished only if traffic was maintained continuously through the Canyon. The reason was simply the lack of suitable alternative routes. While there is considerable fluctuation of traffic volumes throughout the year due to the recreational appeal of western Colorado, the Canyon corridor also serves as a major interstate commerce route and experiences heavy truck activity. Consequently, it is not politically and economically feasible to attempt to close the Canyon to traffic for other than very short periods of time.
2.2 Traditional Approach to Traffic Control

The traditional, and almost universally accepted, approach to traffic control in U.S. highway construction zones is well known. Each construction contractor, whose work interferes with or otherwise affects the traveling public, is required to protect the public and provide traffic control services and equipment as part of his construction contract. The services traditionally include traffic control supervision and flagging while the equipment includes the furnishing and placement of all traffic control devices. The cost of these services and equipment is normally estimated in advance and is included in the schedule of bid items for a particular construction contract. The construction contractor is fully liable and responsible for the proper control and management of these resources in the interest of public safety. Payment to the contractor is based on the number of units of each item actually employed on the project at the unit bid price.

This method of traffic control has been adopted on virtually all highway construction projects involving public funds in the United States. It is normally a very effective method, affording the contractor the flexibility to conduct his operations in a most efficient manner, while ensuring the safety of the public at a reasonable cost. Although normally endorsed, and even mandated, by CDOH and FHWA whenever federal highway construction funds are involved, this practice proved inadequate and ineffective for the construction of I-70 through Glenwood Canyon.

2.3 Early Experience

When the initial construction contracts in the Canyon were awarded in late 1981, they included the normal provisions for traffic control described above. The first contracts were small, limited in number, and confined to areas of the Canyon where adequate workspace was available. Original construction zones were located where the potential for conflicts between the public and construction forces could easily be minimized. Consequently, public traffic encountered minimal delay and hazard exposure.

As the number of contractors increased and construction activities intensified, however, it became readily apparent that the traditional methods would not work. Loss of control, with its inherent safety and operational implications, was imminent unless a completely different approach to traffic control was taken. Given the confined space in the Canyon, it was inevitable that conflicts between contractors and the traveling public, as well as between the contractors themselves, should occur. The proximity of adjacent contractors' work zones, which in some cases overlapped, became a catalyst for intolerable abuse of and delay to, the traveling public.

This situation rapidly emerged as each contractor controlled and indiscriminately stopped bi-directional traffic for the sole benefit of his own operations. While the results were completely unacceptable, this was permissible under the terms of the contract specifications. With no more than two lanes available to move public traffic and to accommodate construction operations, major queues of traffic quickly formed in both directions. The queues developed to the extent that contractors were causing traffic to back up into adjacent contractors' work zones. The resultant condition of gridlock, a term normally reserved to describe extreme traffic congestion in urban areas, manifested itself not only in delays to motorists, but also in the inability of contractors to transport their own equipment and construction materials. By late 1984 and early 1985, it was common for a one-way drive...
through Glenwood Canyon to take as long as two hours during daytime periods of construction activity; most of this delay would be experienced over a distance of only three to four miles (5 to 6.5 km) of construction zone. All traffic was thus subjected to increased hazards and extremely frustrating stop-on-go conditions.

2.4 Need for Special Approach

Even prior to the full development of these unacceptable conditions, officials of CDOH and FHWA recognized the potential for a serious mobility crisis in Glenwood Canyon that would result in unacceptable costs to the public. Not only was the travel delay incurred by the motorists a major concern; consideration had to be given to the increased costs that would have to be absorbed by the project due to reduced efficiencies in contractors' operations (delivery of materials, maneuverability of equipment). More importantly, the issue of handling emergencies, whether in response to accidents in the Canyon or a need to transport accident victims through the Canyon to the hospital in nearby Glenwood Springs had to be addressed. Accordingly, CDOH commissioned its Project Management Consultant, Daniel, Mann, Johnson, & Mendenhall (DMJM), to conduct a comprehensive study encompassing the principal concerns of traffic operations and emergency procedures. This study (Ref. 1), which was published in February 1985, presented conclusions and recommendations to deal with the wide variety of conditions and situations that were expected to develop during the construction process. Although solutions for such secondary concerns as construction logistics and public information programs were presented, the study emphasized a pragmatic, innovative and economically sound approach to handling traffic—one which would minimize delays, mitigate the potential for gridlock in the Canyon, and provide effective emergency response procedures. The result of this controlled traffic condition would be, as was subsequently realized, an unprecedented benefit to both the public and the construction contractors that cannot be overstated.

The key elements of the proposed traffic control plan included:
- A systems approach to coordinating all flagging operations.
- A sophisticated communications network.
- A pilot car operation.
- An umbrella contract that would combine all traditional and special traffic control functions in the Canyon under a single authority.

3. THE SOLUTION

3.1 Interim Test Program

Recognizing that the deteriorated traffic conditions would destroy the credibility of the project in the eye of the public, CDOH was compelled to take immediate and positive action to alleviate the impending chaos. It used the recommendations in the DMJM study as a basis for implementation of an interim test program, which had a reasonable probability of succeeding under the prevailing conditions and which was acceptable to all existing construction contractors.

A contract instrument available to CDOH at the time, and the only one that could be implemented in short order, was the Contract Modification Order (CMO). Since the urgency of resolving the traffic problem left no other recourse, it was decided to initially implement the DMJMJ recommendation by invoking the CMO on an existing and active construction contract. The CMO was issued to a construction contractor with the intent of "testing" the validity and practicality of the study recommendations.
At this time, there were several construction contracts underway in one of the most constricted reaches of the Canyon, having a combined length of about 3.6 miles (6 km). Because of the severe width limitations, each contractor had demonstrated a critical need to limit traffic to a single lane in order to carry out his construction activities. This necessitated conveying all traffic through the constricted zones on a single lane by alternately halting one direction of traffic while the opposing traffic was allowed passage. The concept was credible but the implementation did not work. Therefore, this stretch of the Canyon became the obvious candidate for a “test program”, which was initially implemented under a CMO as Pilot Car Operation (PCO) through this controlled section of the Canyon.

The PCO required the establishment of control points at either end of the controlled section. At these locations, operations personnel held queues of traffic until opposing queues have negotiated the area and passed the control point. Once a moving queue has passed a control point, the stopped queue is released and escorted through the construction zone by a lead pilot car (A). A trailing pilot car (B), following the end of the queue, ensures that no vehicles have stopped and ascertains whether or not gaps have developed in the queue. The drivers of both escort vehicles are in radio contact and can therefore control the speed of the traveling queue in order to minimize gaps.

Under operating conditions, it was quickly learned that the vehicle used as Pilot Car A in one direction could become Pilot Car B for the movement in the opposite direction. This practice evolved when it became apparent that considerable efficiencies resulted by having Pilot Car A proceed past the control point to the end of the stopped queue, turn around, and take up position as the trailing pilot car (B). Similarly, when Pilot Car B reaches the control point, it can easily turn around, take up position at the front of the stopped queue, and almost immediately lead it off as the new Pilot Car A.

The controlled section of the Canyon was divided into 10 equal segments, the ends of which were clearly identified by signs which were used as check points by the pilot car operators. As each pilot car passed a check point, the operator would report its location by radio thus affording all individuals in the operation current information as to the precise location of the queue.

Because of terrain constraints on radio transmissions, all personnel associated with the PCO, as well as individual project Traffic Control Supervisors (TCS) were furnished with mobile or hand-held ultra-high frequency (UHF) radios. These radios offered the advantage of considerably longer range than the citizen’s band (CB) radios which had previously been used and continued to be used for short range communications between project TCS’s and their assigned project flaggers.

The implementation of the PCO mandated a complete role reversal in the duties and responsibilities of the project flaggers. Prior to this test program, the primary function of traffic control personnel was to control public traffic for the benefit of the construction contractor. On each individual construction contract, flaggers controlled traffic to give priority to construction equipment and the performance of construction activities. There was absolutely no coordination between adjacent projects or uniform utilization of controls and procedures. This situation proved to be as frustrating for traffic control personnel as it was for the public and the adverse safety implications were readily apparent.
Under the FCC, the emphasis of project flagging was completely reversed. Flaggers' primary responsibility now was to ensure the safety and convenience of the traveling public by controlling the movement of construction equipment. Flaggers were stationed at all points where contractor operations were taking place. When no traffic was present, such as between queues, equipment operators were free to utilize the entire roadway width if needed. However, when directed by a local flagger, who is in constant communication with his or her TCS and knows where an approaching queue of traffic is relative to that location, the equipment operator would move out of the traffic lanes and restrict his activities to those which would not interfere with traffic. This assured safe and clear passage for the arriving queue.

The success of the FCC was apparent within a few hours of its initiation and exceeded the most optimistic expectations of those who designed and caused the implementation of the program. Early observations revealed the fact that travel time through the construction zone, along with public delays, were significantly reduced; vehicles were stopped less frequently (usually only once); emergency trips through the Canyon were more effectively accommodated; and public response was exceptionally positive. An unanticipated benefit was the fact that construction contractors, some of whom were vehemently opposed to this concept when it was first introduced, began to realize increased efficiencies in the delivery of materials to, and operation of equipment at, the construction sites. As a result of these positive observations, it was decided to continue the "test program" indefinitely until a more formal program could be implemented. There was, however, concern as to how long the FCC would be effective as traffic volumes began to grow later in the year.

3.2 Operational Analysis

Since the test of the FCC was initially conducted during periods of relatively low traffic volumes, it was necessary to gain a complete understanding of the dynamics of the FCC in order to assess its ability to function effectively under the higher summer traffic volumes. Therefore, a large amount of operational data was collected both during the initial test (April 1985) as well as in a subsequent period (June 1985). Reduction and analysis of this data yielded valuable information regarding approach volume, queue length, travel time, speed, discharge time, headway and delay. The types of data collected included the following:

- Traffic Approach Volumes - These are manual counts along with vehicle classifications in order to obtain the combined two-way arrival rates of vehicles throughout the time period of the pilot car operation (7:00 a.m. to 5:00 p.m.). The counts were taken at locations sufficiently removed from the construction zone so that the random arrival pattern of vehicles was not affected.

- Travel Times - The travel time of each queue was determined based on the pilot car operators' radio transmissions of departure and arrival times at the respective control points.

- Discharge/Passage Times - The elapsed time for each queue of traffic to pass a
given point was determined by radio transmissions and was used, along with queue volumes, to determine vehicle densities and headways.

Queue Volumes - The number of vehicles in each queue was recorded manually.

The information gathered in the field was then tabulated in a computer spreadsheet where it was reduced to give the various operational parameters stated above; these are summarized in the following table. (The difference between the combined approach volumes and those actually carried in the queues is attributable to the high number of construction-related vehicles that either do not go as far as the location of the PCO or are allowed to bypass a stopped queue and are therefore not counted.)

**TABLE 1**

**SUMMARY OF OPERATIONAL PARAMETERS**

<table>
<thead>
<tr>
<th></th>
<th>April</th>
<th>June</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined Approach Volumes</td>
<td>3402</td>
<td>4114</td>
<td>+21%</td>
</tr>
<tr>
<td>Combined Queue Volumes</td>
<td>3169</td>
<td>3839</td>
<td>+21%</td>
</tr>
<tr>
<td>Average Queue Volumes</td>
<td>80</td>
<td>96</td>
<td>+20%</td>
</tr>
<tr>
<td>Average No. Queues/Day</td>
<td>35</td>
<td>40</td>
<td>N/A</td>
</tr>
<tr>
<td>Average Speeds (mph)</td>
<td>25.2</td>
<td>26.9</td>
<td>7%</td>
</tr>
<tr>
<td>Average Delays (min.)</td>
<td>12.7</td>
<td>12.4</td>
<td>-2.5%</td>
</tr>
<tr>
<td>Headway (sec.)</td>
<td>4.44</td>
<td>4.10</td>
<td>-8%</td>
</tr>
<tr>
<td>Travel Time (min.)</td>
<td>8</td>
<td>8</td>
<td>N/A</td>
</tr>
<tr>
<td>Passage Time (min.)</td>
<td>5.15</td>
<td>6.21</td>
<td>+20%</td>
</tr>
</tbody>
</table>

Examination of the information presented in the table yielded some interesting patterns which were found to be reliable enough to become the basis upon which to formulate a capacity prediction model. For example, the percent increase in the average number of vehicles per queue from April to June was consistent with the increase in combined two-way approach volumes. Further analysis, utilizing linear regression procedures, revealed that there was, in fact, a direct correlation between approach volumes and queue lengths. The increase in average speeds along with the corresponding decrease in headways, was attributable to the improved efficiency of the PCO after the initial novelty of the operation had become accepted; these parameters did not change materially after this point and were concluded to have stabilized.
Because of the consistency of these operational parameters, the field data were determined to be a valid basis for predicting the Service Rate, or the adjusted capacity of a single lane operating under alternating one-way traffic conditions. In the early stages of implementation of the PCO, it was hoped that a modified traffic signal queueing model would be capable of predicting actual operations. The results, however, were disappointing in that the model did not reflect actual conditions. As is frequently the case with analytical models, it could not be calibrated to duplicate actual field observations. A major misconception was that “breakdown” would occur when the “capacity” of the PCO was exceeded and that specific approach volumes would prevail hour after hour with resultant queue build-ups of uncontrollable proportions.

This, however, was found not to be the case. DMJM, who was responsible for observing and analyzing the operation, developed a projection model based on the simple continuity equation, which revealed that “breakdown” will not occur, even when the approach volumes exceed the service rate of the system. Under the prevailing conditions, it was found that this occurs at an approach volume of about 600 vehicles per hour (total of both directions); yet the model predicted that the service rate would continue to increase at a moderate rate, but less than the rate at which approach volumes increased. The validity of the model was confirmed during periods of considerably higher traffic volumes; the Canyon has never had to be opened to two-way traffic because of high approach volumes during periods that the PCO was in effect, except under unusual (non-traffic-related) emergency conditions. (A detailed analysis of the dynamics of the PCO is available from the author, Ref. 2).

3.3 Limitations of the Test Program

The success, as well as immediate public acceptance, of the PCO left CDOH with no option but to continue the “test program” as long as it was operationally warranted. However, because of administrative complications that could have emerged due to the manner in which the program was structured, a new management approach had to be found. There remained several concerns that had to be addressed and resolved before the Glenwood Canyon Traffic Control Management Program could be considered operationally, administratively and legally acceptable:

- Since no central authority existed to combine and coordinate all traffic control efforts in the Canyon (the PCO encompassed just one segment of the Canyon), there continued to be some adverse operations, resulting in multiple stops and unnecessary delay, due to another construction contract several miles from the PCO. This contract also required frequent traffic stoppages, which were administered independently of the PCO, and frequently resulted in irregular arrival rates at the PCO control point. Occasional releases of traffic from this remote project sometimes happened to coincide, by chance, with the release of queues through the PCO, thus demonstrating that the desired level of coordination can be achieved.

- The PCO test program continued to be operated under a CMO on a single construction contract. This entailed considerable expense over and above what it reasonably should cost. Also, the fact that the personnel involved in the operation were employees of that contractor could be construed by other contractors to imply that preferential treatment was being practiced.
The individuals conducting the PCO, while working as employees of one construction contractor, were making decisions involving the operations of other construction contractors. The propriety of one contractor making contract administration decisions on behalf of CDOH was clearly in question and could have resulted in claims and other legal complications had it not been for the total acceptance and good will of the other contractors. Nevertheless, this potential had to be mitigated.

Recognizing the virtually assured continued success of the PCO, as well as the potential for an even greater measure of traffic coordination throughout the Canyon, CDOH persisted in its endeavor to find an administrative solution that would satisfy these legitimate concerns. Fortunately, the optimum vehicle for implementation of such a program was already in place in the form of the DMJM Management Consulting Contract. All that was required was approval by the appropriate regulating agencies.

3.4 Implementation of the Formal Program

For several years, DMJM had functioned as the Project Management Consultant to CDOH on the Glenwood Canyon project. The contract between DMJM and CDOH was uniquely structured to allow CDOH to manage all aspects of the project without being burdened by normal administrative processes. Among numerous other provisions, this professional services contract stipulated that DMJM personnel could be made available to function as agents of CDOH, subject to appropriate approvals and direction.

Therefore, CDOH exercised its authority to supplement the contract with DMJM for the specific task of providing the traffic control management services that CDOH could not provide from its own in-house resources. The contract with DMJM resulted in the easy implementation of the first steps towards an overall coordinated program. Under this program, DMJM provided the following resources:

1. One individual to function as the Glenwood Canyon Traffic Coordinator (GCTC) who was given the authority to supervise and coordinate all traffic control personnel and operations in the Canyon.

2. A variable number of Operations Personnel (depending upon needs) who have diverse duties which included driving pilot cars; controlling the release of queues from the control points; directing contractor equipment and other authorized vehicles around a stopped queue (when conditions permit); and advising stopped motorists of the status of traffic and construction conditions.

3. A Communications Coordinator who serves as administrative assistant to the GCTC and has the primary responsibility of coordinating between and communicating with all interested parties including law enforcement agencies, emergency response services and news media.

4. All vehicles required to carry out the pilot car operation and those other functions being provided directly by DMJM.

5. The special two-way radios required for communicating throughout the Canyon, including the necessary licenses to operate on assigned frequencies.
Implementation of this first step gave CDOH the immediate advantage of demonstrating to the various contractors the authority of the GCTC, who now acted as a representative of CDOH and not of a competing contractor. This arrangement gave greater credibility to all decisions made by the GCTC since the stigma of preferential treatment was now removed.

While this was being successfully implemented, CDOH began the process of eliminating all remaining traffic control functions from the construction contracts. This was accomplished by the formulation of an "umbrella" traffic control support contract which could be advertised for competitive bidding and would provide the following:

1. Project flaggers to be assigned to the various construction contracts.
2. Traffic control supervisors, usually at least one for each active construction contract, who supervise and direct those flaggers assigned to the respective contract.
3. All traditional construction traffic control devices including signs, cones, channelizing devices and barricades.
4. Field facilities including a field office for the use of the GCTC and information trailers located at strategic points east and west of the Canyon, which were staffed by CDOH employees to advise motorists of conditions in the Canyon.

The provisions of this contract included a time limitation of one year after which time it would be re-advertised for new bids. The reason for this was two-fold. First, it was extremely difficult to estimate the quantities of bid items for much longer than one year in advance. Second, it afforded more opportunities for other pre-qualified traffic control or construction contractors to bid for this work. The first contract of this type was awarded in the beginning of 1986.

The major distinction between the traffic control provisions of this contract and those of a traditional construction contract lies in the area of responsibility. Under the traffic control support contract, all decisions pertaining to the actions and operations of traffic control supervisors and flaggers are made by the GCTC. The GCTC, in fact, has the authority to approve or reject personnel proposed for assignment to the project and enforces the provisions pertaining to the utilization and condition of traffic control devices.

4.0 SUMMARY

4.1 Administrative and Operational Benefits

It was early in 1986 that the entire Glenwood Canyon Traffic Control Management Program was fully operational. CDOH now had total control over all traffic-related matters in the Canyon, the responsibility for which it delegated to DMJM through the professional services contract it had in place. The early operational advantages that were first realized when the PCO was initiated continued to accrue, but with the added benefits derived from an overall management structure that rendered this operation truly unique and effective beyond any expectations.
With a contractual arrangement that was legally and administratively proper and acceptable to the highest authorities, CDOH was in a position to conduct its daily traffic-related operations with the confidence that they were being carried out by responsible professionals acting on behalf, and in the capacity of agents, of CDOH. Furthermore, since these individuals, though employees of DMJM, were in effect making contract administration decisions that are typically and properly the domain of CDOH, the question of the propriety of these actions ceased to be an issue with the construction contractors, who accepted this arrangement with diminishing skepticism.

The direct benefits to the traveling public continued to improve even beyond those initially realized. With a central authority in control of all traffic operations through the entire Canyon, controls on traffic required by construction contracts removed from the zone of major activity could now be fully coordinated with the dynamics of the PCO. It was possible to synchronize, partly because of the sophisticated communications network in place, the stoppages of traffic such that motorists were rarely required to stop more than once. While these stoppages sometimes became lengthy (average delays to motorists were 30 minutes during periods of high traffic volume), public acceptance of this program was enthusiastic and gratifying.

This acceptance, though largely attributable to the improved efficiencies of the new operation, clearly confirmed the value of the extensive public information campaign that evolved as a by-product of this program. Informational signs were placed sequentially on principal approach roadways as far as 60 miles (97 km) from the project, which gave information such as the length of delays to be anticipated and the radio stations on which motorists could be advised of construction and traffic status. Small low-power, remote controlled radio transmitters were installed about 10 miles (16 km) from each end of the Canyon which provided continuous, pre-recorded messages on traffic conditions. These messages could be changed by telephone, as needed, by the communications coordinator based in the traffic control field office.

The most effective public relations strategy was the element of personal contact. This was accomplished by stationing sufficient operations personnel in the Canyon to walk along the stopped queues and talk with each driver, advising them of expected delays and offering information about the project.

Construction contractors benefited greatly from this operation, which afforded their personnel and equipment a degree of mobility not originally thought possible. The fact that traffic was being held only at designated control points, combined with the effective radio communications network, permitted traffic control personnel to systematically guide these construction vehicles through the apparent gauntlet of stopped traffic, moving traffic and active construction zones, with a level of confidence and efficiency that was unprecedented.

4.2 Safety Enhancements

Perhaps the greatest benefit that was realized as a result of this program was the improvement in safety and enhancement of emergency response capability. Given the fact that accident rates are typically higher in construction zones than on comparable roadways not under construction, the relevant statistics in Glenwood Canyon are truly remarkable. Since 1982, the first full year of construction in the Canyon, the accident rate has dropped from a
high of 2.94 accidents per million vehicle miles (MVM) to a low of 0.97 ACC/MVM in 1986, with a slight increase to 1.13 in 1987, the most recent year for which official statistics are available. It should be noted that almost all accidents recorded from 1985 through 1987 occurred during periods when the traffic control operation was not in effect (nights and weekends).

A major concern to all officials had always been the ability to convey emergency vehicles through the construction zones. There is frequently a need for police, ambulances or other emergency response teams to travel from the small towns east of the Canyon to the hospital in Glenwood Springs to the west. During the early years of construction, these vehicles were often helplessly detained in traffic without any opportunity of by-passing the congestion. After implementation of the new traffic control program, emergency vehicles were virtually assured of clear passage through the entire Canyon when advance notice of estimated arrival time was given over the emergency telephone "hot line". At such a time, the entire Canyon is placed on standby until one of the traffic control vehicles has escorted the emergency vehicle through the Canyon. Of course, during these situations there is an understandable and acceptable delay to public traffic.

The safety enhancements that have been experienced are attributable to various factors, including consistency in the enforcement of specifications which set forth traffic control procedures, a vigorous program of information exchange on a rigid schedule, and a mandatory training program of all personnel involved in traffic control. The GCTC and all key traffic control supervisors are required to be certified by the American Traffic Safety Services Association (ATSSA). Of equal importance, the personnel management practices of DMJM have created a high level of morale among its staff resulting in an extremely low turnover of trained and experienced employees.

4.3 Cost Analysis

The cost of providing this sophisticated level of traffic control is somewhat higher than that for traditional traffic control methods on more "typical" highway construction contracts. An analysis of these costs (expressed as a percentage of total project cost) was undertaken for the three-year period 1986 through 1988, both for the Glenwood Canyon project and for the entire State of Colorado. The following summarizes the findings:

<table>
<thead>
<tr>
<th></th>
<th>Construction Cost</th>
<th>Traffic Control Cost</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glenwood Canyon</td>
<td>$104,000,000</td>
<td>$5,489,000</td>
<td>5.26%</td>
</tr>
<tr>
<td>State-wide</td>
<td>$614,000,000</td>
<td>$25,178,000</td>
<td>4.10%</td>
</tr>
</tbody>
</table>

The higher costs experienced in Glenwood Canyon are directly attributable to the amount of labor (flaggers and traffic control supervisors) required on this project. This is not surprising given the fact that the labor represents 80% of total traffic control cost in Glenwood Canyon, while the respective percentage statewide is 60%.

Not included in the above analysis are the costs associated with the traffic control management, including the pilot car operation and the entire public relations/information program.
Over the three-year period, this came to an additional $1,828,000 with a resultant increase in the overall percentage to 7.0%.

CDOH finds these costs acceptable and fully justified when the total benefits of the program are considered. It is probable, but difficult to substantiate, that the cost savings realized due to improved construction efficiencies are far greater than the increase in traffic control costs. Perhaps more significant are the savings that have accrued from the substantially reduced delay to the traveling public. The monetary value of a one-hour delay reduction to as many as 100,000 vehicles per month has cost implications of enormous proportions.

4.4 Limitations and Applicability

Admittedly, the specific method employed to handle traffic in Glenwood Canyon is neither practical nor possible under most other conditions. It would be unacceptable, for example, to routinely stop traffic for up to 30 minutes, or to conduct a pilot car operation in an urban environment. The significantly higher traffic volumes would result in total operational breakdown. In other situations, such as on projects employing only a single contractor, traditional traffic control methods are usually acceptable and are to be recommended.

What has emerged out of the traffic experience in Glenwood Canyon, and which has captured the attention of traffic control professionals nationwide, is the high level of safety and construction efficiency that can be enjoyed through the implementation of a traffic control management program under a single authority. CDOH is convinced that this is the most effective mechanism available for handling traffic on large highway construction projects involving numerous contractors. In its own program to reconstruct 12 miles (20 km) of urban freeway in Denver (with average daily traffic exceeding 150,000 vehicles per day in places), CDOH is committed to utilizing this process, by adopting the Glenwood Canyon program as a model for development of specific traffic control plans, specifications and, ultimately, operations in the field.

The Glenwood Canyon Traffic Control Management Program has achieved a level of success and acceptance that exceeds all expectations. The highest validation that this program could possibly have realized came in September 1986 when it became the recipient of the Transportation Achievement Award for Operations, bestowed upon CDOH and DMJM by the Institute of Transportation Engineers (ITE). To those actively involved in the development and implementation of this unique program, the incredible safety record, operational efficiency and public acceptance provide the impetus to strive for continued improvement despite the ever-present administrative and operational challenges confronting the project.
References:


Safety at Roadworks

Michael Marlow
Transport & Road Research Laboratory (TRRL)
United Kingdom
SAFETY AT ROADWORKS

by M Marlow

Two major studies have been completed by the Transport and Road Research Laboratory. The first updates an examination of the safety performance of major motorway roadworks. The second reviews for the first time, the risk associated with works on all-purpose roads.

The safety of traffic management systems at major roadworks on motorways is monitored at intervals by the Transport and Road Research Laboratory. Developments in maintenance layouts and operation in recent years prompted a new review. The survey covered dual 3 lane motorways in several Counties. A sample of 17 roadwork sites was examined, representing a cross section of major maintenance layouts. Over 63 million vehicle passages totalling 1000 million vehicle kilometres of travel were recorded at the work sites and similar numbers at the same sites when no works were in progress.

Taking all traffic management layouts together over the whole site (ie, the three main elements – approach, contra-flow and after sections combined) personal injury accident rates at roadworks are 1.6 times the no-works rate. The risk associated with each of the three sections through the works are identified, and compared with previous studies. The full range of accident characteristics (eg, by time, weather effects, accident type etc) are also examined. The study showed that the layouts in current use at major roadworks on motorways are still considerably safer than all-purpose roads without works.

In contrast to motorway works, little was known about the effect that roadworks situated on all-purpose roads might have on accident rates. To fill this omission, a three year study was undertaken by TRRL in two Counties. Information was obtained from 155 roadworks, the majority of which were on Trunk and A class single carriageway roads. In spite of the duration of the study, and observations relating to about 100 million vehicle kilometres of travel through the works, only 34 personal injury accidents were recorded. A result, which highlights the difficulty associated with detailed safety studies of this nature, in contrast to similar motorway reviews. However, statistically significant results were obtained, which permitted the increase in accident risk due to roadworks on single carriageway all-purpose roads to be identified.
SAFETY AT ROADWORKS
M Marlow
Transport & Road Research Laboratory, United Kingdom.

1. INTRODUCTION

Roadworks are a common feature on the road network. Their variety is considerable, ranging from major contra-flow systems on busy motorways, lasting several weeks, to minor patching repairs on lightly trafficked rural roads, taking only a few hours. The extent of roadworks and the continuing requirement for them in the future has emphasised the need for safe and efficient methods of managing traffic at work sites. Two major studies have been completed by the Transport and Road Research Laboratory to assess roadwork safety (1,2). The first updates an examination of the safety performance of major motorway roadworks. The second reviews, for the first time, the risk associated with works on all-purpose roads. This paper examines the safety issues arising from maintenance on these two types of road.

2. MAJOR MOTORWAY ROADWORKS

2.1 Background

The safety of traffic management systems at major roadworks on motorways is monitored at intervals by the Transport and Road Research Laboratory. The last study was conducted in 1982 (3). Since then there have been further developments in maintenance layouts and operations, including the general adoption of full contra-flow systems with 2-lane crossovers and lane rental procedures. These changes indicated the need for a new safety review, and a survey was undertaken to collect and analyse accident information from motorway roadwork sites. The objectives were to obtain estimates of accident rates with and without works and to compare them with the national motorway rate.

3. DATA COLLECTION

A study sample of 17 roadwork contracts was chosen from the 40 major maintenance schemes scheduled for 1987/88. This was a cross section of roadworks and reflected the current major maintenance layouts on the motorway network.

Schematic diagrams for the principal types of layout are shown in Figure 1. In the case of the full contra-flow system (example A), all traffic is carried
on one carriageway, with two lanes allocated for each direction. Current practice is to take the primary traffic (that obstructed by the works) across the central reserve in two contiguous lanes (two lane crossovers) to run on the right and centre lanes of the secondary carriageway. The opposing streams of traffic are carried on the left lane and hard shoulder, separated from the primary flow by a 1.3m wide buffer zone. The other frequently used layout is the partial contra-flow (examples B, C, D and E), where only one lane of primary traffic is taken across to the other carriageway, and is separated from the secondary flow either by a buffer zone or a complete buffer lane.

Accident records were requested from the County and city authorities for the contra-flow length and 6 kilometres either side. The accident data collected included, wherever possible, information on the location, date, time, weather conditions, number and severity of casualties, number of vehicles involved, light or dark, cause and/or type of accident, and traffic conditions. In most cases, the listing contained adequate descriptions of the accidents. However, where the County data were inadequate, police accident records were consulted. It should be noted that accidents only appear in the record if they were reported to the police or were discovered by other means, such as a patrol. The earlier study (3) presented evidence to suggest that a very large proportion of personal injury accidents are reported, and this is especially likely to be the case on motorways, given the higher level of police surveillance. In contrast, damage-only accident records can be very unreliable, and, as a result, both the earlier and current studies concentrated primarily on personal injury accidents (PIAs). The possibility that accident observation and hence recording rates may be higher at roadworks than in their absence may be a source of potential bias. No attempt was made to address this aspect in the current review.

Traffic flow data were obtained from the Counties' and Department of Transport sources for both the with-roadworks periods in 1987, and the earlier years when the sections were works free.

4. PERSONAL INJURY ACCIDENT RATES

4.1 Composition of Study Sample.

The 1987 study reviewed 17 roadwork sites, covering 65 roadworks phases, and lying in the areas served by 16 different local authorities (Counties and cities). The majority of the sites employed full contra-flow
traffic management systems with 2-lane crossovers, and three were partial contra-flow layouts with 1-lane crossovers and a buffer zone.

In the study sample, traffic flows ranged from just under 20,000 vehicles per day to nearly 90,000 vehicles per day. Durations of the roadwork phases varied from 5 days to 77 days. Seven of the sites were operated under lane rental procedures, whereby contractors earn a bonus for early completion of the work, or incur a charge if the contract period is exceeded.

Over 63 million vehicle passages, totalling 1000 million vehicle kilometres of travel, were recorded at the work sites, and similar numbers at the same sites when no works were in progress. There were 155 personal injury accidents recorded during the periods with roadworks, compared with 89 in the absence of works.

The 1987 study sample is compared with the 1982 sample in Table 1. Considering all systems together, the number of sites in 1987 is about three quarters of the number in 1982; the total vehicle kilometres in 1987 at roadworks is about two thirds of the 1982 total. This small difference may be due to the shorter durations of roadworks in recent years, encouraged by the adoption of the lane rental procedures mentioned above.

4.2 Overall Personal Injury Accident Rates

Taking all traffic management layouts together over the whole site (i.e. the contra-flow section plus 6 km either side), the PIA rate per million vehicle kilometres is 0.154 (89/910) (Table 1). The equivalent rate without works is 0.098 (155/1010). Thus the ratio of the with-works to no-works accident rates from the 1987 sample is 1.57 (0.154/0.098). This compares with the ratio of 1.45 (0.161/0.111) for the 1982 study sample. The differences between the 1987 and 1982 accident rates are not significant at the 95 per cent level of confidence.

Applying the national motorway personal injury rate per million vehicle kilometres of 0.11 to the overall PIA ratio (the accident rate with works to that without) of 1.6, gives an estimate for the national rate of 0.18 PIA per million vehicle kilometres at motorway roadworks. This compares favourably with the rates, which include junctions, on built-up major (A-class) roads (1.16) and on non built-up major roads (0.34). This reveals that roadworks on motorways in 1987 were still appreciably safer than all-purpose roads without works, when averaged over all traffic
management systems for the whole site.

4.3 Ratios of Personal Injury Accident Rates by Section

Table 2 presents the ratios of the accident rates, by sections of the roadworks layout (Figure 2). The information is grouped by the two main traffic management types, and for the primary and secondary directions of travel, both separately and combined. Data for the 1982 study is also included for comparison.

It can be seen that the 1987 accident rates in the approach and contra-flow sections of the full contra-flow layout sites were statistically different from the no-works rate (Table 2(a)). Compared to the 1982 survey, the 1987 ratios for the approach and contra-flow sections in the primary direction are significantly higher (at 99 per cent confidence level), and lower for the after section, although the difference there is only significant at the 85 per cent level of confidence. A significant increase (at the 99 per cent level of confidence), compared with the 1982 data, was also noted in the ratio for the approach section in the secondary direction. However, there was a reduction in the 1987 ratios for the contra-flow and after sections (Table 2(b)), although the changes from 1982 for these sections are significant at lower levels of confidence (75 and 85 per cent respectively). Taking all layouts, and both directions of travel together, the distribution of accident ratios due to roadworks recorded in the two studies are very similar (Table 2(c)). The contra-flow section showed the highest rises in accident ratio compared with the no-works rate. The approach section also showed a small increase, though the accident ratio in the after section fell.

5. ACCIDENT SEVERITY AND CASUALTIES

As in 1982, accidents recorded in the 1987 sample, with and without roadworks, were grouped by severity. Despite the large scale of this study—covering about 2000 million vehicle-kilometers of travel—the numbers of accidents involved are not large; there were, for example, only 19 fatal accidents in total. Consequently, none of the apparent changes noted below were significant at the 95 per cent confidence level.

The data indicate that at roadworks in 1987, there was a reduction in the proportion of serious injuries, and a corresponding increase in the proportion of slight injuries, with no alteration in the proportion killed. The study data also show that the distribution of
numbers of casualties per PIA by severity was similar, both with and without roadworks.

6. OTHER ACCIDENT CHARACTERISTICS

6.1 Accidents by Time of Day and Week

As noted above in Section 5, the total number of accidents recorded in the study during the intervals with and without roadworks was not large. The further subdivision of these totals by time of day means that the accident numbers in some periods are small, and inferences should be treated with caution. Nevertheless the 1987 results reflect the general pattern of accident rates through the day noted in the 1982 survey, in particular the markedly higher accident rate, both with and without roadworks, between the times 0000 to 0300, compared with that recorded in the other periods of the day. The increase, noted earlier, in the personal injury accident rate at roadworks is apparent for most of the day - over the period from 0600 to 2100 hours, the rate at roadworks is significantly higher (at 95 per cent level). However in the intervals 0300 to 0600 and 2100 to 2400 the 1987 accident rate with roadworks is comparable to that recorded in the absence of roadworks.

Both studies have shown that accident rates increase with roadworks, and the daily rates reflect this result. In 1987 the exceptions are Tuesday and Friday, and Monday in the 1982 study. The Saturday and Sunday patterns noted in the two years' studies are similar, with accident rates at roadworks over the weekend higher than the corresponding rate on weekdays.

6.2 Effect of Road Surface and Weather Conditions

The effect of road surface conditions on the numbers and percentages of personal injury accidents with and without roadworks was also examined. Some 59 per cent of accidents occurred in dry conditions at roadworks in 1987 which compares with the figure of 60 per cent of all accidents occurring in the dry on motorways in Great Britain in 1987.

The results of effect of weather conditions also reflect the national pattern: the figure of 76 per cent of personal injury accidents, both with and without roadworks, recorded as occurring in fine weather is similar to the 77 per cent of all accidents which occur in good weather conditions on the motorway network.
6.3 Accident Types

The types of accidents, both with and without roadworks are shown in Table 3. The results show similar distributions to those observed in 1982, and confirm the earlier finding of the sharp rise in the proportions of nose-to-tail collisions which occur at roadworks compared with the no-works situation.

6.4 Numbers of Vehicles Involved in Accidents

The study showed that accidents at roadworks involve more vehicles. The average number of vehicles involved in each personal injury accident at roadworks was 2.7 (showing little change from the value of 2.5 in 1982); the corresponding figure for the works-free situation was 2.1 (unchanged from 1982). The proportions of accidents in which 4 or more vehicles were involved was 29 per cent at roadworks and 8 per cent without works. This compares with the national proportion for 1987 of 11 per cent.

7. ROADWORKS ON ALL-PURPOSE ROADS

7.1 Background

In contrast to major motorway works, little has been known hitherto about the effects that roadworks on all-purpose roads might have on accident rates. The length and durations of this type of works are generally shorter and the flows much lower than those on motorways. The net result is that the vehicle kilometres contributed by a single roadworks on an all-purpose road is small, and as a consequence, a large number of sites is required to collect a sample of vehicle kilometres, and accidents, of sufficient size. In addition, the works are often less well documented than those on motorways.

8. DATA COLLECTION

With these constraints in mind, a study was initiated in 1983 to investigate accident rates at roadworks on non-motorway links (2). A combination of two methods of collecting the data were used:
- a retrospective method which would involve the use of County records and discussions with officers to determine details of past works; and
- a current method which would involve data being recorded at the time the works took place.

Two counties - the Royal County of Berkshire and the County of Norfolk - were identified as willing to participate in the study and who had appropriate
records. The choice of study sites during the retrospective data collection periods was partly predetermined by the participating counties, whose records for past roadworks were confined to the major ones. However, a full range of roadworks was available during the current stage.

The accident and traffic flow data were obtained for the roadworks period and for a comparable period without the works. The zone of influence, over which the accident data were requested, was assumed to be 1.65 km. either side of the works.

A total of 155 roadworks were sampled in the survey (Table 4). The 37 sites in Berkshire yielded 70 per cent of the sample of vehicle kilometres at roadworks (ie the works zone itself, taken as the roadworks length plus 150 metres each side), during their known periods of operation, with the 118 Norfolk sites contributing the remainder. Taking the two counties together, 80 sites were on major roads (Trunk and A class), with only 8 on dual carriageways. The remaining 75 sites were on minor roads (B and C class).

9. PERSONAL INJURY ACCIDENT RATES

The data collected for the 155 roadworks on all-purpose roads showed marked increases in the personal injury accident rate per vehicle kilometre with the presence of roadworks (Table 5). Most of the increases in accident rate were statistically significant at high levels of confidence, and showed rises which range between 110 to 180 per cent (at 95 per cent, or more, level of confidence). These results apply for lengths of road which include the roadworks zone and up to 1200 metres either side. Thus the PIA ratio (the accident rate with works to that without) on major (Trunk and A-class) single carriageway roads of 2.7 yields an estimate for the national rate of 0.62 PIA per million vehicle kilometres at roadworks on links of this type. This compares with the works-free PIA rate on minor (B- and C-class) links of about 0.45 PIA per million vehicle kilometres.

10. CONCLUSIONS

The data collection methods for roadworks on motorways are straightforward and robust data can be collected over a period of a few months. In contrast, the procedures for all-purpose roads are more complex and time consuming. With only two Counties involved, the collection of sufficient data for a statistically
significant analysis took over three years. However the methods developed proved both cost effective and practical.

The overall results of the two studies may be summarised as follows:
- personal injury accident rates in the presence of major roadworks on 3-lane motorways are 60 per cent higher than in their absence; however
- this risk is less than that encountered on the roadworks-free all-purpose network.
- personal injury accident rates on single carriageway all-purpose major roads rise by about 170 per cent when roadworks are present.

11. ACKNOWLEDGEMENTS

The work described in this Paper forms part of the programme of the Transport and Road Research Laboratory and the Paper is published by permission of the Director. The author would like to thank R. D. Coombe and D. Turner (both of Halcrow Fox and Associates). The cooperation received from the representatives of the various County, Police and Regional Authorities is gratefully acknowledged. Particular thanks are due to the officers of the Royal County of Berkshire and the County of Norfolk, whose help with the all-purpose study over a 5 year period was invaluable.

12. REFERENCES


2. COOMBE R D and D R TURNER. Accidents at Roadworks on All-purpose Roads. TRRL Contractor Report CR150. Transport and Road Research Laboratory, Crowthorne, 1989.


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<table>
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<tr>
<th>TRAFFIC MANAGEMENT SYSTEM</th>
<th>CODE</th>
<th>ROADWORKS SITES</th>
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<td>ACCIDENTS</td>
<td>TRAFFIC</td>
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<td>VEH-KM x 10^8</td>
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</tr>
<tr>
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<td>Buffer zone</td>
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<td></td>
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<tr>
<td>Partial contra-flow</td>
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<tr>
<td>1-lane crossover</td>
<td>B</td>
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<td>4 [31]</td>
<td>2.4 [32.5]</td>
<td>0.4 [5.4]</td>
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<td></td>
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Notes: 1. Figures in square brackets ( ) relate to the 1982 study.
2. Code refers to examples in Figure 1.
3. Accidents are either personal injury accidents (PIA) or damage only (DO); the symbol ‘-’ indicates that no accidents were analysed.
Table 2. Personal injury accident ratios by section

(a) Primary Direction

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<thead>
<tr>
<th>Type of traffic management layout</th>
<th>Layout Code (2)</th>
<th>Approach Section</th>
<th>Contra-flow Section</th>
<th>After Section</th>
<th>Approach and After Sections</th>
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<tr>
<td>2-lane crossovers</td>
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<td>[1.7]</td>
<td>[80%]</td>
<td>[0.3]</td>
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<tr>
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<td>[95%]</td>
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</table>

(b) Secondary direction

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<th>Contra-flow Section</th>
<th>After Section</th>
<th>Approach and After Sections</th>
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</thead>
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<tr>
<td>Full contra-flow, A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-lane crossovers</td>
<td>[1.3]</td>
<td>[85%]</td>
<td>[3.7]</td>
<td>[99.9%]</td>
<td>[0.7]</td>
</tr>
<tr>
<td>Partial contra-flow, D,E buffer zone</td>
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<td>[99.9%]</td>
<td>[1.0]</td>
<td>[99%]</td>
<td>[1.0]</td>
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<tr>
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<td>[99%]</td>
<td>[3.1]</td>
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</table>

(c) Both directions

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<td>2-lane crossovers</td>
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<td>[95%]</td>
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</tbody>
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Notes: 1 The Table elements have the following meaning:
- the first figure is the ratio (with and without roadworks) of the accident rates (PIAs per million vehicle kilometres) for the 1987 study;
- the percentage is the confidence level at which the difference between the with-works rate and the without-works rate is significant;
- the figures in brackets beneath are the corresponding values from 1982 survey.
2 See Figure 1 for examples of these site layouts.
Table 3. Personal injury accident frequency by type of accident

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<thead>
<tr>
<th>TYPE OF ACCIDENT</th>
<th>S</th>
<th>M</th>
<th>T</th>
<th>C</th>
<th>O</th>
<th>L</th>
<th>X</th>
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<td>Number of PIAs</td>
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<td>17</td>
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<td>89</td>
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<td>Percentage of total</td>
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<td>Both</td>
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<td>24</td>
<td>11</td>
<td>3</td>
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Notes:  
S = Shunt  
M = Mechanical failure  
T = Tyre failure  
C = Loss of control  
O = Overtaking error  
L = Struck shed load  
X = Other or unknown
### Table 4  Structure of the all-purpose road data base for 1983/88

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<tr>
<th>SUBGROUP</th>
<th>NUMBER OF ROADWORKS SITES</th>
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<td></td>
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<td>ZONE(2)</td>
<td>ZONE(2)</td>
<td>ZONE(2)</td>
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<tr>
<td>Berkshire</td>
<td>37</td>
<td>170.87</td>
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<td>169.76</td>
<td>244.59</td>
<td>286.15</td>
</tr>
<tr>
<td>B-class</td>
<td>45</td>
<td>75.58</td>
<td>71.71</td>
<td>151.56</td>
</tr>
<tr>
<td>C-class</td>
<td>30</td>
<td>31.54</td>
<td>35.96</td>
<td>35.68</td>
</tr>
<tr>
<td>All Sites</td>
<td>155</td>
<td>387.43</td>
<td>509.03</td>
<td>765.05</td>
</tr>
</tbody>
</table>

Notes:
1. The works zone was taken as the length of the roadworks plus 150 metres either side.
2. The influence zone was taken as 1.5km either side of the works zone.
Table 5. Increases in personal injury accidents at roadworks on all-purpose roads

<table>
<thead>
<tr>
<th>ROAD TYPE AND CLASS</th>
<th>WORKS ZONE ALONE (2)</th>
<th>WORKS ZONE PLUS INFLUENCE ZONE OF 1200M</th>
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<tr>
<td>All Road Types:</td>
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<tr>
<td>Trunk alone</td>
<td>65%(50%)</td>
<td>60%(60%)</td>
</tr>
<tr>
<td>A-class alone</td>
<td>95%(90%)</td>
<td>178%(95%)</td>
</tr>
<tr>
<td>Trunk and A-class</td>
<td>90%(90%)</td>
<td>113%(95%)</td>
</tr>
<tr>
<td>Single Carriageways:</td>
<td></td>
<td></td>
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<tr>
<td>Trunk and A-class</td>
<td>126%(95%)</td>
<td>172%(99%)</td>
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</tbody>
</table>

Notes: 1. Figures in brackets are the confidence levels at which the increases in personal injury accidents at roadworks (shown unbracketted) were significant.

2. See footnote 1 to Table 4.

3. Analyses for B-class and C-class roads separately proved inconclusive.

4. The data were insufficient for an analysis of dual carriageway roads alone.
Figure 1. Standard traffic management layouts
Figure 2. Definitions of site sections
Warning Lights on Service Vehicles in Work Zones

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Transportation Safety Coordinator
Transportation Research Board
U S A

and

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Director
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U S A
Warning lights on service vehicles in moving and short-term work zone operations serve as part of and sometimes as the primary traffic control scheme. This paper reports on a study examining driver information needs in these work zone situations, the impact of various warning light parameters on selected driver behaviors and the effectiveness of several warning light systems in short-term and moving work zone operations.

Various lighting systems (i.e., strobes, rotating lights, flashing lights and a light bar) were field tested. Closed test track results indicated that certain characteristics (e.g., flash rate, number of lights, medium versus high intensity) had little effect on driver closing rate and speed estimating performance. These tests confirmed the importance of information transmission (e.g., directional arrow) in addition to conspicuity. Test track findings also demonstrated that the slower the maintenance vehicle travelled, the more difficulty drivers had in judging closing rate when approaching the rear of the service vehicle.

Actual highway observations were conducted in simulated maintenance activities in three states. Results obtained for stationary short-term lane closures suggest use of rotating light and flashing light combinations on service vehicles. Arrow boards were effective for lane closures.

For moving maintenance operations the rotating light plus flashing light, the Ohio (two headlight size lights in a flashing mode) light and the light bar were most effective. However, the light bar was not as effective in stationary operations. Again, arrow boards were also effective.

While a shadow vehicle following a moving maintenance operation at 500 feet was highly effective, it was considered optional due to its expense. A simple cost-benefit model was developed to help decide when shadow vehicle use was warranted.

The product of this research was guidelines for warning light use on service vehicles in eleven categories of short-term and moving work zone operations.
WARNING LIGHTS ON SERVICE VEHICLES IN WORK ZONES

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and

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Director
Transportation Research Corporation
Haymarket, Va USA

1. INTRODUCTION

Short-term and moving maintenance or utility operations should not be treated like long-term, stationary work zone operations for several reasons.

a. Solutions to long-term work zone traffic control may be far too time consuming and costly for short-term or moving operations.

b. A traffic control scheme used for stationary operations may create an unnecessary hazard for a moving operation.

c. Constantly changing traffic control systems for short-term operations may create more driver confusion and more worker exposure to hazard than simpler systems.

d. Research on long-term work zones has focused on ground-based traffic control systems. Short-term and moving operations are likely to be service vehicle based. Current research in the United States on traffic control systems does not adequately address lighting or marking characteristics for vehicle-based traffic control systems from the perspective of driver behavior.

Previous research on traffic channelizing devices for long-term maintenance operations (1) has been incorporated into traffic control manuals. However, that work does not encompass moving or short-term operations, for example, warning light systems for service trucks. A project has been funded to develop empirically based guidelines for states, counties, and cities in the United States for traffic control and warning devices to be used in short-term and moving maintenance operations.

This paper reports on the first objective of that project: to develop guidelines for warning light systems on service vehicles engaged in short-term or moving maintenance operations.

The research was performed by evaluating existing warning light systems on the basis of three main criteria. First, the warning lights must elicit driver responses leading to safe (or safer) traffic operations. Second, the warning lights must be efficient to use, (i.e., require minimal manpower or electrical power) and must be reliable. Finally, the warning light system must be cost-effective.
1.1 Literature Review

Lighting of service and emergency vehicles, railroad grade crossings, vehicle rear lighting, and other signaling studies were reviewed. A clear finding from this review is the lack of uniformity in the United States of lighting regulations and of standardization across cities, counties, and states (2). This leads motorists and pedestrians to confuse emergency and service vehicles. There is also considerable lack of standardization in light parameter measurement, a problem not addressed by this project.

In 1979 Lum (3) reported that the standard four-way flasher was effective in reducing the hazard in overtaking other vehicles. Reaction distance, speed reduction and vehicle following characteristics were all improved by this device. Tobey and Knoblauch (4) found similar results on freeways, and Lyles (5) also found the four-way flasher warning lights effective on slow-moving vehicles.

Color and number of lights were compared by Berkhout (6) in a field experiment. Red lights were generally superior to blue, and monochromatic lights were superior to combinations of red and blue in the same light. Twin lights outperformed single beacons, and light bars fared better than single lights. Most important, a trade-off was noted between conspicuity and information transfer. Lights that were conspicuous in the road environment did not have the best information transfer characteristics.

Studies of railroad grade crossings, locomotive conspicuity, and rear lighting did not reveal any conclusive evidence that strobe, halogen, or rotating versus flashing lights were superior for service vehicle applications.

1.2 Other Background Information Sources

State maintenance manuals were reviewed. Few states had guidelines for warning lights specific to short-term or moving maintenance operations.

A survey of state traffic and maintenance engineers identified commonly used warning light devices and configurations. High energy consumption and excessive and difficult to perform repairs were the problems most often mentioned. Intense flashback from strobe lights during snowfall and unnecessary use or misapplication of arrowboards were mentioned frequently. Motorists colliding with the rear end of snowplows and slow-moving maintenance trucks and drivers overslowing in response to blue warning lights were a few of the behavioral problems noted.

A survey of available lighting devices was made from manufacturer's catalogs.

1.3 Work Zone Classification

On the basis of an analysis of short-term and moving maintenance activities and of the driver information requirements resulting from encountering those activities, a
A decision aid for categorizing work zones was devised. As Figure 1 shows, eleven categories of short-term or moving work zones can be identified on the basis of duration of maintenance activity, location of the operation, need for lane closure, lane to be closed, traffic volume, and type of roadway. Each of these categories has unique driver information requirements for traffic control devices, warning lights, or both.

1.4 Problem Identification

A common denominator among the several sources of background information was that drivers fail to recognize that service vehicles are moving more slowly than their own vehicles (or are stopped). Over the years there has been a movement to increase conspicuity of lights and markings by increasing brightness, number of lights, etc. However, the question of information content—how well drivers can determine closure rate or speed of the preceding vehicle—has seldom been addressed.

Two experiments were performed in a closed field setting to determine how effective existing warning lights are in prompting drivers about closure rate and speed of a service vehicle.

The first experiment examined type and intensity of light, type of light motion, and flash rate in day and night settings and at different service-vehicle and following-car speeds. The second experiment studied current and new light placements or configurations on the service vehicle and different combinations of lights.

Selected lighting systems were then tested in operational roadway settings.

2 CLOSED FIELD EXPERIMENTS

2.1 Overview of Closed Field Experiment Methodology

The test site was an unopened 3,000-foot section of four-lane divided and marked concrete roadway. One end was rural and the other passed over an Interstate highway.

Ninety-six people were tested, 48 in each experiment. Within each experiment, 24 people were tested at night and 24 during the day. An even division of subjects (Ss) by sex and age (25 percent 16 to 24 years old, 50 percent 25 to 54 years old and 25 percent over 55) was generally but not perfectly achieved.

The experimental procedure had five Ss riding in a van at 35 or 55 mph. Ss were seated behind a large window shade. At 35 mph, the shade went down for 4 seconds, revealing a dump truck (freshly painted orange) 350 feet ahead moving at 4, 14, or 28 mph. At 55 mph, the shade was lowered when the van was 750 feet behind the truck. A different warning light treatment was used on the truck at each viewing. Reliability measures were taken at the beginning and end of each experiment to ensure that the truck and van spacing and speeds were correct.
FIGURE 1 Decision aid to categorize short-term and moving maintenance operations.
Errors were consistently less than .9 second. Ss responded to the warning lights by choosing one of ten speed categories they could be travelling and rating how fast they were closing on the service vehicle.

The thirteen lighting treatments tested in Experiment 1 are listed in Table 1. Nine combinations of lights (listed in Table 2) plus the five placement configurations shown in Figure 2 were tested in Experiment 2.

Table 1. Lighting Treatments for Experiment 1

(Mounted on top and center of dump truck bed tailgate door unless otherwise noted)

- 2 four-way flashers—mounted at the bottom of dump bed
- 4 four-way flashers—two at bottom and two above dump bed
- Single-flash strobe light—high intensity, 360-degree visibility
- Double-flash strobe light—high intensity, 360-degree visibility
- 3 x 5 foot arrowboard
- 2 small arrows, 24 x 20 inches each, mounted on dump bed door, both pointing in same direction and flashing together
- Rotating 100-120 cpm, medium intensity, incandescent
- Rotating 100-120 cpm, high intensity, incandescent (halogen)
- Rotating 60-80 cpm, medium intensity, incandescent
- Rotating 60-80 cpm, high intensity, incandescent (halogen)
- Flasher, 60-80 cpm, medium intensity, incandescent
- Flasher, 100-120 cpm, medium intensity, incandescent
- Flasher, 100-120 cpm, high intensity, incandescent

Note: Only one treatment was visible to the subject at a time.

FIGURE 2
Placement/Configuration for Light Treatments in Experiment 2
<table>
<thead>
<tr>
<th>Lighting Combinations for Experiment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 2 back-and-side mounted rotating 60-80 cpm, medium-intensity</td>
</tr>
<tr>
<td>1 front-center-mounted strobe (double flash)</td>
</tr>
<tr>
<td>- 2 four-way flashers</td>
</tr>
<tr>
<td>1 front-center-mounted strobe</td>
</tr>
<tr>
<td>- 4 four-way flashers</td>
</tr>
<tr>
<td>1 front-center-mounted strobe</td>
</tr>
<tr>
<td>- 2 back-and-side-mounted, rotating 60-80 cpm, medium intensity</td>
</tr>
<tr>
<td>1 front-center-mounted flasher, 100-120 cpm, high intensity</td>
</tr>
<tr>
<td>- 2 four-way flashers</td>
</tr>
<tr>
<td>2 rotating front-side-mounted, 60-80 cpm, medium intensity</td>
</tr>
<tr>
<td>- 4 four-way flashers</td>
</tr>
<tr>
<td>1 rotating front-center-mounted, 60-80 cpm, medium intensity</td>
</tr>
<tr>
<td>- 4 four-way flashers</td>
</tr>
<tr>
<td>1 flasher, front-center-mounted, 100-120 cpm, high intensity</td>
</tr>
<tr>
<td>- 2 four-way flashers</td>
</tr>
<tr>
<td>1 3x3-foot arrowboard</td>
</tr>
<tr>
<td>- light bar, sequenced flashing, six lights</td>
</tr>
</tbody>
</table>
2.2 Findings From the Closed Field Experiments

The estimate of service vehicle speed made by Ss is not a direct measure of the correctness of the information transmitted to the driver. Therefore, a correctness score was derived by comparing Ss speed estimate with the actual service vehicle speed. These data were analyzed using measures of central tendency, analysis of variance for repeated measures, and nonparametric procedures.

First, there were no statistically significant differences in order of treatment presentation, day vs. night, and length of test session (S's change in response due to fatigue).

Five general findings emerged from the two closed-field studies.

1. If only one type of light is used, four-way flashers provide the most accurate information about closure rate and service vehicle speed.
2. Adding more of the same type of lights on the service vehicle does not increase the amount of information provided to the driver or enhance the driver's ability to extract information from the lights.
3. Changing the location of the light(s) on the service vehicle does not increase information or ability to extract information.
4. Flash rates between 60 and 100 cpm, and medium vs. high intensity lights had little effect on driver response.
5. Adding a four-way flasher to any other warning light increases the amount of information provided to the driver. Similarly, combining a roof-mounted flasher light and rotating light increases the information input to the driver.

The very short flash(s) of a single or double strobe do not provide information to the same degree as the longer cycle times of the incandescent flashers.

The two experiments only concerned information extraction. Conspicuity or attention value was not measured. The attention value of a high intensity strobe light, of a rotating light, or of an arrowboard is important. Once attention is gained, it seems important to provide more complete closure rate and speed differential information through a flashing light component.

Another result from the closed field experiments is that the speed of the service vehicle has more impact on driver closure rate and vehicle speed judgment than the warning lights. This effect is most severe at the very low (4-8 mph) service vehicle speeds.

3. OPERATIONAL HIGHWAY TESTS

Warning lights were tested in an operational setting on two and four-lane and four-lane divided (Interstate) roadways. Tests were conducted in three states (northern, mid-south, and southern). The lights were used in short-term and moving operations.
3.1 Test Method

At each of the seven test sites, the experimental paradigm consisted of three conditions: before treatment, treatment applied, and treatment removed. For the before and removed-treatment conditions, the state’s current standard operating equipment, e.g., warning lights, was used. The during treatment condition involved one of the project proscribed warning lights. Each treatment was observed at a minimum of two test sites. Highway conditions included a variety of maintenance operations. Observations were made during the day and under sunny and cloudy conditions.

The measure of effectiveness was "lane change time." This measure takes into account that preferred vehicle-mounted warning devices result in earlier avoidance behavior by approaching drivers. Two specific applications of this measure were (a) mean lane change time—average value for the specific test condition and (b) critical lane change time—tenth-percentile value to indicate lane change occurrence dangerously close to the maintenance operation. These measures were calculated for free flow and impeded traffic, for trucks and non-trucks, and for shoulder and mainline maintenance operations. These were, of course, segregated according to moving or short-term operation.

Field data were gathered in simulated maintenance operations; unobtrusive observers stationed on maintenance vehicles coded lane change times into specially programmed hand-held computers. A sample of 27,784 behavioral observations was made.

3.2 Short-Term Lane Closure Operations

Four lighting systems were tested: light bar, two rotating lights plus one flashing light, double flash strobe, and four-way flashers plus one cab-mounted flashing light.

Analysis of variance statistics indicated the most effective light compared with the baseline condition was the two rotating lights plus one flashing light. Slight benefits came from use of the light bar and no benefits were associated with the double flash strobe light or four-way flasher plus cab-mounted flasher.

3.3 Moving Maintenance Operations

Five lights were tested: light bar, two rotating lights plus a flasher light, double flash strobe, four-way flasher plus single flasher, and two side-mounted 8 inch flasher lights (nicknamed the Ohio Light). (This last light was used in an attempt to test an existing light with potential to have both the flasher information transfer characteristics and higher brightness, and hence conspicuity, than four-way flashers.) The tests were run at 8 mph.
In this scenario the light bar was the best warning light compared with the baseline lights. Good but not as effective as the light bar were the two rotating-plus-flasher and Ohio Light treatments. The four-way flasher plus single flasher produced minor benefits. The double flash strobe showed no benefits.

3.4 Shoulder Operations

Neither an arrowboard (in flashing bar mode) nor the two rotating beacons plus flasher reduced traffic speed past the shoulder work zone. Both lighting treatments elicited lane shifts, but this may not be a benefit if there is no concurrent speed reduction.

3.5 Ambient Light Conditions

There were no operationally useful differences in lighting systems between the cloudy and sunny ambient light conditions.

4 DISCUSSION AND CONCLUSIONS

Considering the closed field and operational highway testing, there is no perfect consensus of results. However, there are no sharply divergent results, so the possibility of providing operational guidance based on these results is feasible.

4.1 Operational Guidelines

For each of the eleven short-term or moving maintenance operations, lighting system guidelines were developed. These can be summarized as follows:

For a short-term lane closure, two rotating beacons plus a single flasher should be used.

For continuous moving operations, two rotating beacons plus a flasher is suggested. Even though the light bar outperformed this treatment, it was not as effective in the lane closure situation. Although the Ohio Light was effective, it was not tested in the short-term setting. The light bar and Ohio Light need additional testing before they would be the warning light of choice.

For shoulder operations, service vehicle lighting should be used as a warning system under extreme conditions, e.g., limited sight distance, and poor lateral clearance.
4.2 Light Characteristics

The type of light and method of flashing were the two characteristics that had the greatest impact on light effectiveness within the intensities and flash rates studied. Number and placement of lights had little impact on driver response to the warning lights. However, the key to light placement is that the device be visible from all angles at which drivers might approach the service vehicle.

4.3 Conclusions

As the closed field tests demonstrated, certain warning lights do not contribute to the driver's perception of the hazard of a slow moving or stopped service vehicle. In fact, a few of the lights actually degraded the driver's perception of closure rate or service vehicle speed, others were neutral, and a small number improved driver perception, (i.e. the drivers erred on the safe side). The operational message of these findings is that selection of a warning lighting system does have safety consequences and is ideally done on the basis of empirical results.

Although the above research did produce suggested practice, there is clearly a place for additional operational testing of known devices. Also, development of a warning light system that maximizes both conspicuity and information transfer should be encouraged.

5 REFERENCES


Analysis of Statistical Data on HFV-Accidents and Vehicle Measures to Improve Safety

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Federal Highway Research Institute
Federal Republic of Germany
U. Stöcker

Analysis of statistical data on HFV-accidents and vehicle measures to improve safety

The analysis provides a survey of heavy freight vehicle (HFV) populations, tonne-kilometres and accident involvement in different European countries. The official data on HFV-accidents, in most cases based on police investigations, do not include the variety of variables required to justify measures to reduce the number of accidents of this vehicle category. Answers to this type of question may be found through at scene accident investigations.

In the field of passive and active safety, especially as regards freight vehicles, intensive research and development work has been carried out during the last few years. Substantial results from this work are included in national and international Regulations (EEC, ECE). Some measures in the regulations are considered as standard equipment as e.g. the rear underride protection. Other measures are still at the stage of development and/or introduction, e.g. the ALS, the equipment with safety belts, the equipment with additional mirrors. A third series of measures are under discussion, such as the introduction of lateral underride protection devices.
ANALYSIS OF STATISTICAL DATA ON HFV-ACCIDENTS AND VEHICLE MEASURES TO IMPROVE SAFETY

by

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Federal Highway Research Institute
Bergisch Gladbach - Germany

1. INTRODUCTION

Freight transport on roads has steadily risen in Europe in the past years. Accidents and the consequences of accidents involving heavy freight vehicles (HFV) do not show exactly the same trend in development. The number of accidents did not change much with the increase in tonne-kilometers, but the number of critical injury accidents (fatalities and major injuries) fell considerably. Accidents being a multi-causal phenomenon /1/, any change in accidents cannot be explained by individual measures undertaken to improve road safety. Safety measures are mostly introduced en bloc so that ascribing the safety benefits to any one of these measures introduced is a difficult undertaking.

The factors of possible influence on accidents roughly fall into the following three categories: On the one hand, there are the environmental parameters including road network, population and its distribution, topography and weather conditions. Then there are influencing factors relating to the human being, his training, working conditions and licencing conditions. The third group of influencing factors relate to the motor vehicle, roughly to be classified as measures to improve passive and active safety. Passive safety, e.g., includes the seat belt and certain vehicle features to reduce accident severity. Active safety includes measures as for example the breaking system and questions concerning visibility.

Besides the primary category just mentioned, there is also the question --which however is not dealt with here-- of the possible influence on road safety of changes in basic economic conditions. In the U.S. it was found, that the pressures from deregulation measures can be so great on some businesses, that they skip necessary technical inspections for reasons of costs. In the long run this will affect the road-worthiness of entire vehicle fleets.

Considering the accident statistics of individual countries, different survey practices and definitions have to be taken into account when interpreting these statistics. After all statistics are never free from mistakes, a fact reflected by the unreported numbers or transcription errors. Absolute transfrontier comparisons of data are thus not possible and the information provided can only be considered as indicating trends in development.
2. BASIC DATA

The basic data rounding off and facilitating the classification of accident data include information on the size of the country under consideration, its population, network size, population of vehicles to be considered and their relation to road traffic as a whole. In the case of heavy freight vehicles, tonne-kilometres and the mileage of the vehicles are of importance.

A global view of the size, population and road network of different European countries is shown in Fig. 1. In most countries motorways have a share of between 1 and 2% of the overall road network. The proportion of national roads on average amounts to about 10%. In some countries, such as Norway, Spain and Italy, the percentage share of national roads in the total road network is disproportionally high compared with other countries. Relating the total length of the road network to the size of a country, we obtain the density of the road network. Belgium has the densest road network in Europe, with 4.2 km per square meter of area clearly outdistancing the Netherlands (2.76), Luxembourg (2.0) and the Federal Republic of Germany (1.97) which come next. The trends in the development of HFV populations for the time period between 1981 and 1987 is shown in Fig. 2. In general it can be said that there have been increases in the population of HFVs. However, the figures additionally include definitions according to the weight or power classes, which are the classification criteria needed for their inclusion in the statistics. These definitions vary greatly between the countries. The statistical definition of "heavy freight vehicle" often is also linked with the driving licence law. In the Federal Republic of Germany, the HFV statistics,

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<th>Country</th>
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Figure 1: Area, population and road network of selected European countries, 1987 /2/

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showing 1.3 million vehicles in 1987, include delivery vans and trucks and tractor-trailers. Vehicles less than 1 tonne of payload amount to 480,000 and in the payload class between 1 and 4 tonnes there are 549,000 vehicles. Drawing the dividing line between trucks and heavy freight vehicles at a payload of 4 tonnes, a population of 276,000 HFVs would remain. This is the classification used in the French statistics. Otherwise there would have been about 3 million vehicles. This also demonstrates the work that will have to be accomplished when streamlining the databases on an all-Europe-basis. The relationship between HFVs and passenger cars in EC countries is given by the ratio of 1 : 10 (12 million HFVs to 112 million passenger cars).

A survey of the vehicle-kilometers of trucks is given in Fig. 3. The average mileage of these vehicles varies widely in the countries considered. To obtain the true picture, the definition of the vehicle categories on which the figures are based is necessary, here too. Let us have a look at the Federal Republic of Germany to demonstrate the difficulty. The average mileage of all trucks in 1987 amounted to 23,000 km/year. Considering semi-trailers, their mileage alone comes to 82,000 km/year. This shows that vehicles with high payloads and overheads remain longer on the road than others. The figures shown are estimated in many cases so that, also in this context, inaccuracies have to be taken into consideration.

In Fig. 4, total freight in terms of tonnes is summarized ... tabular form. Here the figures increased in all countries in the time period 1981 - 1987. In the middle European countries, e.g., Italy, France and the Federal Republic of Germany, the overall freight figures are comparable. The difficulties of definition
Table 1: Mileage [km/a]

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Figure 3: Mileage [km/a]

Table 2: Million Tonnes

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Figure 4: Million Tonnes

with respect to the freight vehicles, which at other places resulted in differences in vehicle populations, do not play a role here.

3. ACCIDENT REGIME

The mass and structural stiffness of trucks compared with passenger cars are of great influence on the accidents they are involved in and especially on the accident consequences. Car
occupants in a crash with a HFV are affected by 40 times the mass of the car and structural components of a much greater stiffness and are thus much more vulnerable than truck occupants. High-risk accidents for truck occupants are single-vehicle accidents and accidents involving other trucks.

Fig. 5 shows a survey of accident fatalities in Europe for the time period 1980 - 1987. In some countries, considerable success in reducing the figure of fatalities has been attained. For example, a reduction from 13,041 to 7,697 was achieved in the Federal Republic of Germany, one from 6,239 to 5,125 in Great Britain and from 1,998 to 1,485 in the Netherlands. In these figures the passenger car plays an equally dominant role as it does in the accident regime.

The number of truck occupants killed in accidents are summarized in tabular and graphical form in Fig. 6 and 7. Apart from a few countries, a uniform trend in development can generally not be established. This can probably be explained by the relatively low absolute numbers in some of the countries (for example, in those of northern Europe). For that reason, accidents involving more than one fatality significantly influence the overall figure. Within the framework of the research efforts made by the S7-Group /6/ "Role of Heavy Freight Vehicles in Traffic Accidents", a survey of truck accidents and the other road users involved in these accidents has been conducted in OECD member countries. Some of the results are the following: As shown in Fig. 8, passenger car occupants who are many times more affected by accident consequences than all the other road users play a dominant role, even considering the overall number of killed truck occupants included for reasons of comparison. The numbers of fatally injured motorcycle users, cyclists and pedestrians also are conspicuously high.

Figure 5: Total traffic fatalities /4/

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**Figure 6:** Killed HFV occupants /4/

**Figure 7:** Killed HFV occupants (selected countries) /4/

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Information on particular high-risk collisions involving trucks can only be obtained by means of at-the-scene accident investigations. In the Federal Republic of Germany, investigations of this nature are carried out in the greater Hannover area. The results are shown in Fig. 9 have been obtained based on 216 accidents /7/ involving trucks of more than 7.5 tonnes. According to these studies, 47% of all collisions involved HFVs and passenger cars, 23% were truck-truck accidents and 20% truck-motorcycle accidents. The remaining 10% represent pedestrian accidents and collisions with fixed obstacles. The majority of all car-truck accidents are side collisions. Rear-end accidents are predominant in truck-truck collisions and in motorcycle-truck accidents, the motorcycle in most cases crashes into the side structure of a truck. In all truck-car accidents, only 15% of the
car drivers remained uninjured while 98 % of the truck occupants
did not suffer any injuries. In the accidents involving motorized
two-wheelers, 82 % of the riders suffered critical injuries (AIS* greater than 3). In the truck-truck accidents, 90 % of the
occupants either did not suffer any injuries or the injuries
sustained were classified as minor or relatively serious (up to
AIS 2).

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* AIS = Abbreviated Injury Scale

Figure 9: Type of collision and frequency of HFV involvement
(> 7.5 tonnes) /6/

4. MEASURES TO IMPROVE THE SAFETY OF HEAVY FREIGHT VEHICLES

4.1 Legal regulations

The most important legislation in all countries is the vehicle
code. Among other regulations, vehicle codes include standards and
other regulations relating to the construction and equipment of
motor vehicles. Violations of these regulations are followed by
the withdrawal of homologations or type approvals or automatic
expiration of operating permits.
The success achieved in the harmonisation of the framework legislation for motor vehicles is largely due to the efforts of the EC and ECE. Important technical regulations in this context are EEC directives and ECE regulations. EC-member states are bound by the general objectives of EEC directives, but are generally free to apply them as they see fit. However, they have the contractual obligation to harmonize the national legislation with the general aim of the EC. In principle, it is not the task of the EC to set up uniform technical requirements with respect to vehicle safety. Its main objective is the overcoming of trade barriers.

In many cases the contents of EEC directives are in agreement with those of ECE regulations. The overall objective of the U.N. Economic Commission for Europe is the harmonization of technical standards for motor vehicles in Europe. ECE regulations apply to equipment parts only not to the approval of entire motor vehicles. In contrast to EEC directives, there is no obligation for a signatory state to adopt a new regulation. An agreement will take effect only if it is accepted by the state's signature. A comparison of some ECE regulations and EEC directives is given in Fig. 10, also indicating the ECE regulations endorsed by the states in each case. The regulations represent a selection applying to active and passive car safety elements.

<table>
<thead>
<tr>
<th>EEC Directives</th>
<th>Excerpt from the list of countries complying with ECE Regulations</th>
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<tbody>
<tr>
<td>Seat belts 77/541/EEC 1)</td>
<td>R 16 X X X X X X X</td>
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<tr>
<td>In the driver's cab of goods veh.</td>
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<td>R 43 X X X X X</td>
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<tr>
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</tr>
<tr>
<td>Rear underrun protective devices 70/221/EEC 3)</td>
<td>R 58 X X X</td>
</tr>
<tr>
<td>Lateral protection</td>
<td>R 73 X X</td>
</tr>
<tr>
<td>View</td>
<td></td>
</tr>
<tr>
<td>Rear-view mirror 71/127/EEC 2)</td>
<td>R 46 X X X X X X</td>
</tr>
<tr>
<td>Headlamps 76/761/EEC 4)</td>
<td>R 1 8,20 X X X X X X X X</td>
</tr>
<tr>
<td>Position lamps, rear, stop lights 76/758/EEC 4)</td>
<td>R 7 X X X X X X X X X</td>
</tr>
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<td>Fog lights 76/762/EEC 4)</td>
<td>R 19 X X X X X X X X</td>
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<td>R 38 X X X X X X X X</td>
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<td>Steering system 70/311/EEC</td>
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</table>

actual revisions
1) 87/354/EEC
2) 85/647/EEC
3) 81/333/EEC
4) 87/354/EEC

Figure 10: Selected EEC directives and ECE regulations relevant for safety /7/
4.2 Some vehicle measures from the viewpoint of accident research

The underride guard for trucks is selected here as an example from the area of passive car safety. Representing an energy absorbing element, it has gained considerable importance, especially for passenger cars colliding with the rear-end of trucks. It is now a mandatory standard equipment part of trucks, in principle ready for series production, although there are still possibilities for optimization. The basic requirements are laid down in the EC directive 70/221/EEC and the ECE R 58 respectively.

Side guards for trucks mainly serve for the protection of two-wheel riders and pedestrians. The majority of accidents involving these road user groups are fatal because the initial crash is followed by the rider or pedestrian being overrun by the truck. The basic requirements for side guards are laid down in the ECE Regulation R 73. For an optimization of these features the following should be taken into consideration:

- The open rail concept with the rails spaced widely apart exposes unprotected road users to the risk of getting stuck and being dragged along after the crash.

- At Berlin Technical University /9/ studies have shown that a continuous flat surface placed low above the ground appears to be the only design protecting especially cyclists from being overrun after a crash.

A side guard whose lower surface is at least 550 mm above the ground, as has been envisaged thus far, is still too high above the ground to afford the protection desired. Wherever possible, the ground-to-lower surface distance should not be greater than 300 mm. Restrictions with respect to the range of application should be considered, e.g. for construction equipment. Side guards consisting of a continuous flat surface low above the ground have the following all-embracing protection advantages:

- protection of pedestrians and cyclists due to their function as a deflection guard;

- underride guards for cars;

- decrease in the risk of reduced visibility by mitigating spray;

- improvement to the aerodynamics resulting in a reduction of fuel consumption.

The drawbacks are the following:

- limited access to certain vehicle components;
- slight reduction in loading capacity and increased fuel expenses due to the increase in dead weight;
- restrictions concerning the ramp angle;
- increase in purchase costs.

With respect to a front guard for trucks, binding regulations do not yet exist. The protective effect of front guards would mainly benefit car occupants. The energy absorbing deformation element provides collision parties with a crush zone due to which the peak forces released in a crash can be reduced. This would also prevent passenger cars from being forced underneath the front of the truck and the front structure of the truck from penetrating the occupant compartment. Basic studies for the development of a front guard were undertaken in the Federal Republic of Germany at the beginning of the eighties by the HUK association in cooperation with Berlin Technical University /10/. First estimates revealed that the use of a truck front guard system would result in the survival of about 8 - 10 % of the persons killed in frontal crashes with trucks without such protection features, and in the prevention of major injuries to about 2000 people.

The energy absorbing systems suitable for truck front guard systems would be honeycomb structures or a design concept based on a hydraulic damping equipment.

Besides the passive safety of HFVs, its safety in all operating conditions also plays an important role. Driving dynamics and braking systems determine their safety level. The development of improved braking systems including anti-lock braking (ALS) and anti-skid starting reducers (ASR) for trucks and buses enabled raising the safety level considerably. In view of these advances in braking mechanics, the EC issued a directive (88/194/EEC) making the equipment of trucks and buses exceeding 16 tonnes with ALS mandatory.

On a national basis, the Federal Republic of Germany has gone beyond the framework legislation, making the equipment of trucks and buses exceeding a total weight of 3.5 tonnes with ALS mandatory (German vehicle code). This measure was backed by a study which revealed that 7.1 % of all accidents could have been entirely avoided if vehicles had been ALS-equipped. In addition, considerable less material damage and injuries would have been caused due to the overall decrease in damage. The benefits of ALS in preventing accidents and reducing accident consequences are thus quite clear. The benefits have been found to be due to

- maintaining driving stability;
- reducing the braking distance.
Apart from ensuring the necessary braking efficiency in emergency situations, the braking efficiency over longer stretches of difficult road conditions, such as extended downgrade sections, must be ensured. Conventional braking systems can fail in extreme situations of this nature. For the transport of dangerous goods, the equipment of trucks with suitable high-efficiency braking systems has been called for. The engine braking system provided by today's engine concepts does not ensure the required deceleration. For that reason additional equipment, such as the hydrodynamic or electromagnetic retarders have to be used. They operate on the principle of a turbo-engine or that of an eddy current brake and can be adjusted to any driving situation by means of a number of switching steps. Important in this context is their integration into the ALS system to avoid overbraking in adverse weather conditions (e.g. icy patches).

5. SUMMARY

HFVs are relatively safe in accidents as far as drivers and passengers are concerned, as long as crashes with rigid obstacles or other objects of comparable mass are avoided. The number of passenger car occupants affected in accidents with HFVs is many times greater than that of HFV occupants. For example: the passive safety of trucks could be much improved by equipment components affording protection in side and frontal crashes. An optimized side guard would considerably reduce the accident consequences for motorized two-wheelers, cyclists and pedestrians. A front guard system would protect passenger cars from underriding the front of a truck causing the front of the truck structure to penetrate the occupant compartment. The requirements for braking systems to improve the active safety of motor vehicles have lately become stricter and stricter. The introduction of ALS for HFVs also provided an approach to the solution of facilitating braking in difficult situations. An improvement going even further would be attained by solutions enabling a better continuous braking efficiency.

6. REFERENCES


Vehicle and Driver Factors in Relation to Crash Involvement of Heavy Trucks

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VEHICLE AND DRIVER FACTORS IN RELATION TO CRASH INVOLVEMENT OF HEAVY TRUCKS

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ABSTRACT

For a two-year period large truck crashes on the interstate system in Washington State were investigated using a case-control method. For each large truck involved in a crash, three trucks were randomly selected for inspection from the traffic stream at the same time and place as the crash but one week later. The effects of truck and driver characteristics on crashes were assessed by comparing their relative frequency among the crash-involved and comparison sample trucks. Truck configuration, truck equipment condition, and driving hours were the dominant factors associated with increased crash risk. Double trailer trucks were consistently overinvolved in crashes by a factor of three regardless of driver age, hours of driving, cargo weight, or type of fleet. Driving in excess of eight hours increased the risk of crash involvement by a factor of two; drivers with logbook violations, young drivers, and interstate drivers also had increased crash risks. Trucks with defective equipment were overinvolved in crashes. Trucks with brake defects had a crash risk one and one-half times that for truck without brake defects. Trucks with steering defects had a risk that was at least twice that of trucks without defects.
Large trucks (10,000 lbs. gross vehicle weight or greater) are a major safety problem on the nation's highways.\(^{(1,2)}\) They are involved in about 6 percent of all police reported crashes but account for 12 percent of all fatal crashes.\(^{(3)}\) Each year, about 4,800 people die in truck crashes, and almost 75 percent of these fatalities are to people in a vehicle other than the truck.\(^{(4)}\) Trucks are overrepresented in severe crashes, but on a per mile basis trucks appear to have fewer crashes than cars because they travel predominantly on interstate highways, which are low risk roads.\(^{(1)}\) However, when car and truck crashes are compared on similar roads, trucks have higher crash rates.\(^{(5)}\) In recent years, both the number of crashes and the percentage of fatal crashes involving large trucks have been increasing.\(^{(6,7)}\)

Previous studies that have attempted to look at factors that contribute to large-truck crash involvement have been limited because traditional measures of exposure, such as miles traveled or vehicles registered, cannot accommodate analyses of multiple factors. To identify the various factors contributing to large truck crashes, the Insurance Institute for Highway Safety conducted a case-control study in Washington State. This paper summarizes the results of this work.\(^{(8,9,10)}\) The effect of truck configuration on crash involvement is examined, and the paper then focuses on tractor-trailers to look at driver characteristics, especially fatigue, that may affect truck involvement in crashes. Finally, the effects of truck equipment condition on crash involvement are examined.
METHOD

Washington State has allowed a diversity of truck configurations including western doubles, Rocky Mountain doubles, and truck-trailers as well as tractor-trailers, tractors (bobtails), and single unit trucks to operate on all its roads for more than 25 years (Figure 1). The state provides a wide variety of climate and terrain ranging from the temperate coastal region through the Cascade Mountains to the desert areas in the eastern part of the state. The study was conducted primarily on Interstate 5, which carries north-south traffic, and Interstate 90, which has east-west traffic. The data were collected over a two-year period from June 1984 through July 1986.

Truck data were collected by the Commercial Vehicle Enforcement Section (CVES) of the Washington State Patrol. Approximately 100 officers are responsible for the weight enforcement and inspection programs in the state, which includes weigh stations on interstates and other major routes as well as port-of-entry weigh scales. The officers conduct detailed inspections of truck equipment including brakes, steering, tires, and other major systems. They also provide assistance to the State Patrol in the investigation of truck crashes. Truck inspections followed the procedures detailed by the Commercial Vehicle Safety Alliance (CVSA) and the National Uniform Driver-Vehicle Inspection Manual.\textsuperscript{(11)}

Study Design

In this application of the case-control method, for each crash-involved truck, three trucks were selected and inspected at the crash site at the same time of the day as the crash but one week later. Thus, a case sample
of crash-involved trucks and a control (comparison) sample matched for roadway, time of day, and day of week were established. The study included all crashes involving trucks with gross vehicle weight rating greater than 10,000 pounds that occurred on the interstate highway system and involved property damage of at least $1,500 or personal injury. Each crash-involved truck was inspected by a CVES officer to check the condition of the major truck components including brakes, steering, and tires. Where possible, quantitative measures of performance were used; for example, brake adjustment was measured from pushrod travel and tire condition from the tread depth. Truck weight, size, configuration, and type of carrier were also recorded together with driver age and experience, hours of driving, and logbook violations. Hours of driving was recorded as the number of hours driven since the last eight hour rest period. This was established at the time of inspection by the CVES officer who used the driver's statement, logbook record, bill of lading, and current vehicle location to determine a credible estimate of driving hours. This estimate was also used to establish whether the logbook record was accurate; however, the most common logbook violations were either that it was missing or that it was not up to date.

One week after each crash, the CVES officers conducted a random roadside truck inspection at the crash location. For every crash involved truck, three trucks were selected for the comparison sample. The only criterion for selection of comparison sample trucks was that they have a gross vehicle weight rating of 10,000 pounds or greater. Each comparison truck selected was inspected following the same procedures used for the crash-involved trucks. The study included 676 crashes involving 734 large trucks that occurred between June 1984 and July 1986.
Data Analysis

The variables used in the overall analyses included truck configuration, age of driver, weight of load, hours of driving, logbook violations, carrier operation (intrastate versus interstate), carrier type (common, contract, and private), and truck equipment condition. If a variable of interest was unknown for a crash-involved truck, then both crash and comparison trucks were excluded from the particular analysis.

To examine the simultaneous effects of the various study factors, a matched logistic regression model was used to estimate the adjusted odds ratio for each of the factors included in the model. The odds ratio is the odds of crash involvement given a particular factor divided by the odds of crash involvement in the absence of that factor. To fit the model, the logistic regression procedure MCSTRAT from the SAS Users Group International (SUGI) Supplemental Library was used.

Because driver characteristics and truck equipment condition cannot be assumed to be independent of truck configuration, the analyses of these factors were limited to tractor-trailers. Tractor-trailers comprised 60 percent of the crash sample. Limiting the analysis to crashes involving tractor-trailers required that the control sample also be limited to tractor-trailers. Because trucks were randomly sampled, eliminating control cases that were not tractor-trailers did not bias the sample. This subset represents 332 matched case-control data sets.

With a case-control study of this type it is only possible to compute relative involvements, which cannot be converted into crash rates. Consequently, the results from this study cannot be directly compared to
other studies that compute crash involvement rates on a per miles traveled basis. Also, because the crash-involved trucks were compared with randomly sampled trucks, if one value of a variable (e.g., a particular truck configuration) is overrepresented in the crash sample, some other values of the same variable must be underrepresented. By definition, every overinvolvement in the crash sample must be balanced by underinvolvement. Thus overinvolvements or underinvolvements are relative to the overall involvement of large trucks in crashes on the interstate highway system.

RESULTS

Truck Configuration

Table 1 shows the distributions of the crash-involved trucks and comparison sample trucks by configuration. Tractor-trailers were involved in 59 percent all of crashes, doubles (including Western and Rocky Mountain doubles) in 21 percent, truck-trailers in 9 percent, and single unit trucks 8 percent. The corresponding figures for the comparison sample are 59 percent tractor-trailers, 7 percent doubles, 5 percent truck-trailers, and 23 percent single unit trucks. Thus, among large trucks, the crash experience of tractor-trailers parallels their exposure on the road, whereas doubles and truck-trailers are significantly overrepresented in the crash sample and single unit trucks are underrepresented.

To examine the effects of truck configuration in relation to other operating characteristics Table 2 gives the crude and adjusted odds of crash involvement by the various study factors. Truck configuration is the dominant effect; after adjusting for the other study factors, the relative
crash risk for doubles was more than three times that for tractor-trailers. Type of carrier operation (interstate versus intrastate), driver age (<30), driving hours (>6), and load (empty versus full) all showed significantly higher adjusted odds. The adjusted odds for carrier type, fleet size, and body type were not significant.

**Driver Characteristics**

Because driver characteristics could vary across truck configuration, the detailed analyses of driver characteristics were limited to tractor-trailer crashes. Table 3 gives the distribution by hours of driving for the crash and comparison sample for all crashes and for single vehicle and multiple vehicle crashes. Ten percent of crash involved drivers had exceeded eight hours of driving compared to 6 percent of drivers in the comparison sample, so that the risk for drivers exceeding eight hours relative to drivers driving less than two hours was 1.8. The effect was also significant for multiple vehicle crashes (2.6 relative risk) but not for single vehicle crashes indicating the effect of fatigue is more prevalent in multiple vehicle crashes.

**Logbook Violations**

Table 4 gives the distribution of logbook violations and out-of-service logbook violations for tractor-trailers in the crash and comparison samples. Twenty-two percent of drivers of crash-involved trucks had a logbook violation and 8 percent had a logbook violation severe enough to put the driver out of service; the corresponding figures for the comparison sample were 10 percent and 2 percent. The risk of crash involvement
(unadjusted odds ratio) for trucks with logbook violations relative to those with no violations was 3.0, and, if the violation was severe enough to put the truck out of service, the risk increased to 4.2. The relative risk appeared to be consistent across crash configuration for any violations and for out-of-service violations.

Relative Risk of Crash Involvement for Various Driver Characteristics

Table 5 gives the crude and adjusted odds ratios for hours of driving and other driver and truck factors. The dominant effects are driving in excess of eight hours, driver age 30 years or less, and interstate carrier operations. Other factors that appear to increase the relative risk of crash involvement are empty trucks and trucks operating as contract carriers.

Table 6 gives the adjusted odds ratios for the various driver and truck factors with driving hours replaced by logbook violations. Drivers with logbook violations, young drivers, and interstate trucks all show significant increased relative risk of crash involvement. Empty trucks and contract carriers show an increased risk but the effects are not significant.

Truck Equipment Defects

Table 7 gives the distribution by crash configuration of crash-involved tractor-trailers that had defective equipment compared to the matched comparison sample of trucks. Results are for all defects irrespective of type and for brake, steering, and tire defects. Equipment defects sufficient to constitute a violation are given separately from those
that were more serious and sufficient to place the truck out of service; the two figures add to give the total number of defects. Overall, 77 percent of crash-involved tractor-trailers had at least one defect violation compared to 66 percent of the comparison sample trucks, and the relative risk of crash involvement for trucks with defective equipment compared to trucks with no defects was 1.7. Forty-one percent of crash-involved tractor-trailers had at least one defect sufficient to put them out of service compared to 31 percent of the comparison tractor-trailers, and the relative risk of crash involvement for trucks with out-of-service defects was 1.9.

Trucks with brake defects were present in 56 percent of the crash sample compared to 44 percent of the comparison sample such that the relative risk of crash involvement for trucks with brake defects was 1.6. The relative risk for trucks with out-of-service defects (1.7) appeared to be only slightly higher than for trucks with violation defects (1.5). The relative risk of crash involvement for trucks with steering defects was 2.0, which is a higher risk than for trucks with brake defects, although the frequency of occurrence is less; 21 percent of trucks in the crash sample had steering defects compared to 12 percent in the comparison sample. Trucks with tire defects did not appear to have an increased relative risk of crash involvement.

Relative Risk of Crash Involvement for Various Truck Operating Factors and Equipment Defects

Although trucks operating with equipment defects are overinvolved in crashes, it has already been shown that other factors also affect truck crash involvement. The combined effects of these other factors and equipment defects were analyzed, and the adjusted odds ratios for each factor are
given in Table 8 for all crashes and all defects. Equipment defects sufficient to warrant a citation (violation defects) were analyzed separately from the more severe out-of-service defects.

Trucks with equipment defect violations were overinvolved in crashes (relative risk = 1.6, p < 0.06). For trucks with out-of-service equipment defects, the relative risk of crash involvement was even higher (2.0) and statistically significant. The relative risk (1.8) for trucks with at least one defect was also statistically significant.

The adjusted odds ratios for the three categories of equipment defects (brakes, steering, and tires/wheels) were also analyzed as separate factors. Trucks with one type of defect were also likely to have other defects such that the three defect variables are to some extent correlated. This was particularly true for steering and tire defects. Because brake defects were so prevalent, trucks with steering or tire/wheel defects were also likely to have brake defects. However, by separately analyzing trucks that had only one type of defect, an assessment of the individual effects could be made. Table 9 gives the percentage distribution of trucks with defects, for the crash and comparison sample, separated into mutually exclusive groups. Preliminary analyses were made with each of these categories separated into violation and out-of-service defects; however, only steering defects showed any appreciable difference in relative risk between these groups. Thus the categories were combined for brake and tire/wheel defects. The adjusted odds ratios in Table 9 were computed taking into account the confounding effects of driving hours, driver age, carrier operation, carrier type, load, and power steering.
The relative risk of trucks that had brake defects only (1.6) was slightly lower than for trucks with brake defects combined with either steering (2.8) or tire/wheel defects (3.1). For trucks with steering defects only, the relative risk for out-of-service defects appears higher (8.7) than for trucks with violation defects (3.6). For trucks with steering and brake defects, the relative risk (2.8) appears lower than either of the individual steering defect estimates. However, for this combined defect group, the steering defects were predominantly violation defects and the brake defects predominantly out-of-service defects so that this estimate would be expected to be closer to that for steering violation defects. Trucks with only tire/wheel defects had a relative risk of crash involvement that was not significantly different from trucks without these defects. Trucks that had both brake and tire/wheel defects had a higher relative risk than trucks with either individual effect. It should be noted that the confidence intervals for all of these estimates overlapped.

DISCUSSION

This study was designed to look at multiple truck operating characteristics in relation to crashes. A case-control methodology was chosen because, unlike the more traditional methods using crash rates based on vehicles registered or miles traveled, driver and truck factors could be measured simultaneously in both the crash and comparison samples and then compared directly. Looking at multiple truck operating characteristics there were three dominant factors: truck configuration, truck equipment condition, and driving hours. The results show that double trailer
configurations have a much higher crash frequency than tractor-trailers. However, a net benefit might be realized if this increase in crash frequency could be offset by substantial decreases in truck traffic because doubles' greater cargo carrying capacity reduces total truck mileage. The National Research Council study of double trailers estimated that their increased use would reduce combination truck mileage by about 10 percent. This reduction in mileage clearly does not compensate for the up to threefold increase in crash involvement of doubles over tractor-trailers.

The study also showed that tractor-trailers with defective equipment are significantly overinvolved in crashes. Sixty-six percent of tractor-trailers on the Washington interstate system sampled at the same time as crash-involved tractor-trailers had defective equipment warranting a citation, and 31 percent of tractor-trailers had defective equipment warranting placing the truck out of service. The relative risk of crash involvement for trucks with these types of defects was almost twice that of those in good condition. Clearly, truckers need to be made aware that operating with defective equipment is a serious safety hazard to themselves and other road users. Reducing the number of trucks with defective equipment would be likely to reduce truck crashes substantially. This might be achieved by requiring rigorous annual truck inspections, which would ensure that all trucks were in good condition at least once per year; frequent random inspections of truck equipment so that truckers operating defective equipment are less likely to go undetected; and more severe penalties for violators. The combination of a reasonable chance of being inspected plus significant fines for violators should convince many truckers that operating with defective equipment is not only unsafe but also uneconomic.
In addition to truck configuration and truck equipment condition driving long hours also had a substantial effect on crash involvement. In 10 percent of crash-involved tractor-trailers, the drivers had exceeded eight hours behind the wheel. Because the data were collected by asking the driver how long he had been driving, these estimates of driving hours are probably very conservative. Six percent of drivers in the comparison sample, which represents a random sample of trucks taken at the same time of day as the crash-involved trucks, exceeded eight hours driving. However, although the number of drivers spending more than eight hours behind the wheel in these two samples may not appear large, it is important to remember that none of these drivers had reached their final destination. This means that the proportion of drivers who would eventually drive long hours is much greater.

Ten percent of comparison sample tractor-trailers had logbook violations and the increased risk of crash involvement for these trucks was 3.0. It is reasonable to conclude that much of this increase in crash risk is associated with fatigue brought about by operating long hours. Comparing this increased risk with the 1.8 for drivers exceeding eight hours driving, it is clear that the effect for drivers with logbook violations is considerably higher. Also the 10 percent of drivers in the comparison sample with logbook violations must represent a low estimate. These drivers typically had no logbook or the entries were not current rather than falsified logbook entries. It is generally accepted that cheating on logbooks is a common occurrence, and these violations would not be included in the estimate unless sufficiently blatant for the inspection officer to detect them at the time of inspection.
Clearly truck drivers who have been driving long hours or have logbook violations have an increased risk of crash involvement. It is also evident that interstate drivers, who are likely to drive long hours, have a higher crash risk compared to intrastate drivers. Both these problems could be addressed by requiring on-board recording devices in trucks. These devices monitor driving hours and rest schedules, which is advantageous to both drivers and fleet operators. Shippers and fleet managers would be less likely to set schedules that force drivers to drive excess hours to complete trips, because cheating on the hours-of-service regulations would be much easier to detect. Consequently, those drivers obeying the regulations would be much less likely to be at a competitive disadvantage as they are with the present system. Most importantly, many of the crashes involving fatigued drivers should be eliminated.

ACKNOWLEDGEMENTS

Chief George Tellevik and Captain David Boyd of the Washington State Patrol for their support and enthusiasm throughout the project; Officer John Balcom for advice in the early stages; Officer Linda Wilson for coordinating data collection; and all the officers of the Washington State Patrol for their conscientious and expert collection of the truck data.

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REFERENCES


### Table 1

Distribution of Crash-Involved Trucks and Control Sample Trucks by Configuration and Crash Type

<table>
<thead>
<tr>
<th>Crash Type</th>
<th>Distribution of Truck Configurations (Percent)</th>
<th>Total* Number of Trucks</th>
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<tr>
<td></td>
<td>Single Unit</td>
<td>Tractor Only</td>
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<td>All Crashes</td>
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<td>Comparison Sample</td>
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<tr>
<td>Rear End**</td>
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<td>8</td>
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<td>Sideswipe**</td>
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<td>Comparison Sample</td>
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<td>4</td>
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* Some totals do not equal 100 percent due to rounding.

** Truck struck other vehicle.
<table>
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<td>Single Unit</td>
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<td>(0.32, 0.71)</td>
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<td>Doubles</td>
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<td>(2.20, 3.87)</td>
<td>3.17</td>
<td>(2.33, 4.31)</td>
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<td>Others</td>
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<td>(0.87, 1.60)</td>
<td>1.40</td>
<td>(0.99, 1.97)</td>
</tr>
<tr>
<td>(Tractor-Trailers)***</td>
<td>(1.0)</td>
<td>(1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Load</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empty</td>
<td>1.37</td>
<td>(1.10, 1.70)</td>
<td>1.05</td>
<td>(0.79, 1.38)</td>
</tr>
<tr>
<td>Partial</td>
<td>0.63</td>
<td>(0.51, 0.78)</td>
<td>0.83</td>
<td>(0.64, 1.08)</td>
</tr>
<tr>
<td>(Full)</td>
<td>(1.0)</td>
<td>(1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Body Type (N=602)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flatbed</td>
<td>1.13</td>
<td>(0.90, 1.42)</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>0.99</td>
<td>(0.79, 1.25)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Van)</td>
<td>(1.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Driver Age (N=604)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;30</td>
<td>1.21</td>
<td>(0.98, 1.49)</td>
<td>1.51</td>
<td>(1.20, 1.92)</td>
</tr>
<tr>
<td>(&gt;30)</td>
<td>(1.0)</td>
<td>(1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hours Driving (N=555)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1-2)</td>
<td>(1.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-5</td>
<td>1.43</td>
<td>(1.12, 1.83)</td>
<td>1.25</td>
<td>(0.96, 1.62)</td>
</tr>
<tr>
<td>&gt;6</td>
<td>1.49</td>
<td>(1.13, 1.97)</td>
<td>1.32</td>
<td>(0.99, 1.76)</td>
</tr>
<tr>
<td><strong>Carrier Operation (N=603)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interstate</td>
<td>2.02</td>
<td>(1.61, 2.54)</td>
<td>1.54</td>
<td>(1.17, 2.02)</td>
</tr>
<tr>
<td>(Intrastate)</td>
<td>(1.0)</td>
<td>(1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Carrier Type (N=603)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private</td>
<td>0.48</td>
<td>(0.38, 0.60)</td>
<td>0.86</td>
<td>(0.66, 1.14)</td>
</tr>
<tr>
<td>Contract</td>
<td>1.78</td>
<td>(0.91, 1.52)</td>
<td>1.34</td>
<td>(1.01, 1.77)</td>
</tr>
<tr>
<td>(Common)</td>
<td>(1.0)</td>
<td>(1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fleet Size (N=506)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-5</td>
<td>0.78</td>
<td>(0.61, 1.01)</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>6-25</td>
<td>1.03</td>
<td>(0.81, 1.31)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(&gt;26)</td>
<td>(1.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* These variables were not included in the adjusted odds model because the crude odds ratios were not significant.

** Matched logistic regression: 554 matched cases in adjusted model.

*** Reference group is given in parenthesis; the odds ratio are computed within each group.
Table 3
Percentage Distribution of Tractor-Trailers in Crash and Comparison Samples by Crash Configuration and Hours of Driving*

<table>
<thead>
<tr>
<th>Crash Type</th>
<th>Hours of Driving</th>
<th>Crash Sample Percent</th>
<th>Comparison Sample Percent</th>
<th>Crude Odds Ratio</th>
<th>Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>0-2</td>
<td>34</td>
<td>36</td>
<td>1.0</td>
<td>(1.0)</td>
</tr>
<tr>
<td>N=300</td>
<td>&gt;2-5</td>
<td>37</td>
<td>37</td>
<td>1.2</td>
<td>(0.82, 1.69)</td>
</tr>
<tr>
<td></td>
<td>&gt;5-8</td>
<td>19</td>
<td>21</td>
<td>1.0</td>
<td>(0.67, 1.61)</td>
</tr>
<tr>
<td></td>
<td>&gt;8</td>
<td>10</td>
<td>6</td>
<td>1.8</td>
<td>(1.01, 3.22)</td>
</tr>
<tr>
<td>Single Vehicle</td>
<td>0-2</td>
<td>46</td>
<td>38</td>
<td>1.0</td>
<td>(1.0)</td>
</tr>
<tr>
<td>N=93</td>
<td>&gt;2-5</td>
<td>30</td>
<td>35</td>
<td>0.7</td>
<td>(0.34, 1.23)</td>
</tr>
<tr>
<td></td>
<td>&gt;5-8</td>
<td>14</td>
<td>20</td>
<td>0.5</td>
<td>(0.22, 1.09)</td>
</tr>
<tr>
<td></td>
<td>&gt;8</td>
<td>10</td>
<td>7</td>
<td>1.0</td>
<td>(0.36, 2.96)</td>
</tr>
<tr>
<td>Multiple Vehicle</td>
<td>0-2</td>
<td>27</td>
<td>35</td>
<td>1.0</td>
<td>(1.0)</td>
</tr>
<tr>
<td>N=207</td>
<td>&gt;2-5</td>
<td>41</td>
<td>38</td>
<td>1.6</td>
<td>(1.05, 2.54)</td>
</tr>
<tr>
<td></td>
<td>&gt;5-8</td>
<td>21</td>
<td>21</td>
<td>1.5</td>
<td>(0.90, 2.62)</td>
</tr>
<tr>
<td></td>
<td>&gt;8</td>
<td>11</td>
<td>6</td>
<td>2.6</td>
<td>(1.25, 5.18)</td>
</tr>
</tbody>
</table>

* Percentage distribution from unmatched data; crude odds ratio calculated using matched sets.

Note: Reference group is 0-2 hours of driving; the odds ratios are computed within crash type.
### Table 4
Percentage Distribution of Tractor-Trailers
In Crash and Comparison Sample by
Logbook Violations by Crash Configuration*

<table>
<thead>
<tr>
<th>Crash Type</th>
<th>Violations</th>
<th>Crash Sample Percent</th>
<th>Comparison Sample Percent</th>
<th>Crude Odds Ratio</th>
<th>Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Any</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All crashes (N=332)</td>
<td>No</td>
<td>78</td>
<td>90</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>22</td>
<td>10</td>
<td>3.0</td>
<td>(1.97, 4.41)</td>
</tr>
<tr>
<td>Single-Vehicle (N=109)</td>
<td>No</td>
<td>70</td>
<td>87</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>30</td>
<td>13</td>
<td>3.3</td>
<td>(1.74, 6.12)</td>
</tr>
<tr>
<td>Multiple-Vehicle (N=223)</td>
<td>No</td>
<td>83</td>
<td>92</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>17</td>
<td>8</td>
<td>2.8</td>
<td>(1.63, 4.64)</td>
</tr>
<tr>
<td><strong>Out-of-Service</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Crashes (N=332)</td>
<td>No</td>
<td>92</td>
<td>98</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>8</td>
<td>2</td>
<td>4.2</td>
<td>(2.05, 8.70)</td>
</tr>
<tr>
<td>Single-Vehicle (N=109)</td>
<td>No</td>
<td>91</td>
<td>98</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>9</td>
<td>2</td>
<td>4.3</td>
<td>(1.31, 14.05)</td>
</tr>
<tr>
<td>Multiple-Vehicle (N=223)</td>
<td>No</td>
<td>93</td>
<td>98</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>7</td>
<td>2</td>
<td>4.2</td>
<td>(1.68, 10.41)</td>
</tr>
</tbody>
</table>

* Percentage distribution from unmatched data; crude odds ratios calculated using matched sets.

Note: Reference group is no logbook violation; odds ratios are computed within crash type.
Table 5
Crude and Adjusted Odds Ratios of Relative Risk of Crash Involvement of Tractor-Trailers by Hours of Driving and Other Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Crude Odds Ratio</th>
<th>Confidence Interval</th>
<th>Adjusted Odds Ratio</th>
<th>Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driving Hours (N=300)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0-2)**</td>
<td>1.0</td>
<td>(1.0)</td>
<td>1.0</td>
<td>(1.0)</td>
</tr>
<tr>
<td>&gt;2-5</td>
<td>1.2</td>
<td>(0.82, 1.69)</td>
<td>1.2</td>
<td>(0.80, 1.76)</td>
</tr>
<tr>
<td>&gt;5-8</td>
<td>1.0</td>
<td>(0.67, 1.61)</td>
<td>1.0</td>
<td>(0.75, 1.98)</td>
</tr>
<tr>
<td>&gt;8</td>
<td>1.8</td>
<td>(1.01, 3.22)</td>
<td>1.8</td>
<td>(0.97, 3.47)</td>
</tr>
<tr>
<td><strong>Driver Age (N=332)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤30</td>
<td>1.7</td>
<td>(1.20, 2.31)</td>
<td>1.6</td>
<td>(1.09, 2.37)</td>
</tr>
<tr>
<td>(&gt;30)</td>
<td>(1.0)</td>
<td></td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td><strong>Fleet Size (N=278)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-5</td>
<td>0.9</td>
<td>(0.61, 1.31)</td>
<td>1.0</td>
<td>(0.64, 1.51)</td>
</tr>
<tr>
<td>6-25</td>
<td>0.9</td>
<td>(0.64, 1.25)</td>
<td>1.0</td>
<td>(0.67, 1.38)</td>
</tr>
<tr>
<td>(&gt;25)</td>
<td>(1.0)</td>
<td></td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td><strong>Load (N=331)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empty</td>
<td>1.1</td>
<td>(0.73, 1.58)</td>
<td>1.3</td>
<td>(0.84, 2.08)</td>
</tr>
<tr>
<td>Partial</td>
<td>0.8</td>
<td>(0.54, 1.07)</td>
<td>0.9</td>
<td>(0.57, 1.29)</td>
</tr>
<tr>
<td>(Full)</td>
<td>(1.0)</td>
<td></td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td><strong>Carrier Operation (N=331)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intrastate)</td>
<td>(1.0)</td>
<td></td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Interstate</td>
<td>1.8</td>
<td>(1.23, 2.68)</td>
<td>1.7</td>
<td>(1.06, 2.57)</td>
</tr>
<tr>
<td><strong>Carrier Type (N=332)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Common)</td>
<td>(1.0)</td>
<td></td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Contract</td>
<td>1.3</td>
<td>(0.91, 1.80)</td>
<td>1.3</td>
<td>(0.88, 1.98)</td>
</tr>
<tr>
<td>Private</td>
<td>0.6</td>
<td>(0.43, 0.89)</td>
<td>0.7</td>
<td>(0.48, 1.14)</td>
</tr>
</tbody>
</table>

* Matched logistic regression; 265 matched cases in adjusted model.
** Reference group is given in parentheses; the odds ratios are computed within each factor.
Table 6

Adjusted Odds Ratios of Relative Risk of Crash Involvement for Tractor-Trailers by Logbook Violations and Other Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Adjusted Odds Ratio*</th>
<th>Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logbook Violation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any (None)**</td>
<td>2.6</td>
<td>(1.62, 4.01)</td>
</tr>
<tr>
<td>(None)**</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Driver Age</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;30</td>
<td>1.5</td>
<td>(1.01, 2.16)</td>
</tr>
<tr>
<td>(&gt;30)</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Fleet Size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-5</td>
<td>0.9</td>
<td>(0.62, 1.44)</td>
</tr>
<tr>
<td>6-25</td>
<td>1.0</td>
<td>(0.69, 1.42)</td>
</tr>
<tr>
<td>(&gt;25)</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empty</td>
<td>1.3</td>
<td>(0.84, 2.07)</td>
</tr>
<tr>
<td>Partial</td>
<td>0.9</td>
<td>(0.59, 1.32)</td>
</tr>
<tr>
<td>(Full)</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Carrier Operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intrastate)</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Interstate</td>
<td>1.7</td>
<td>(1.11, 2.62)</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Common)</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Contract</td>
<td>1.3</td>
<td>(0.89, 1.99)</td>
</tr>
<tr>
<td>Private</td>
<td>0.8</td>
<td>(0.52, 1.23)</td>
</tr>
</tbody>
</table>

* Matched logistic regression; 277 matched cases in adjusted model.
** Reference group for each factor is given in parentheses; the odds ratios are computed within each factor.
Table 7
Percentage Distribution of Tractor-Trailers with Defective Equipment in Crash and Comparison Samples

<table>
<thead>
<tr>
<th>Type of Defect</th>
<th>Number*</th>
<th>Percent With Defective Equipment</th>
<th>Crude Odds Ratio**</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Crash Sample</td>
<td>Comparison Sample</td>
<td></td>
</tr>
<tr>
<td>All Defects</td>
<td>231</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Violation Defect</td>
<td>36</td>
<td>35</td>
<td>1.5</td>
<td>(0.96, 2.25)</td>
</tr>
<tr>
<td>Out-of-Service Defect</td>
<td>41</td>
<td>31</td>
<td>1.9</td>
<td>(1.28, 2.90)</td>
</tr>
<tr>
<td>All Defects</td>
<td>77</td>
<td>66</td>
<td>1.7</td>
<td>(1.17, 2.46)</td>
</tr>
<tr>
<td>Brake Defects</td>
<td>260</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Violation Defect</td>
<td>26</td>
<td>22</td>
<td>1.5</td>
<td>(1.03, 2.20)</td>
</tr>
<tr>
<td>Out-of-Service Defect</td>
<td>30</td>
<td>22</td>
<td>1.7</td>
<td>(1.19, 2.46)</td>
</tr>
<tr>
<td>All Defects</td>
<td>56</td>
<td>44</td>
<td>1.6</td>
<td>(1.19, 2.18)</td>
</tr>
<tr>
<td>Steering Defects</td>
<td>242</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Violation Defect</td>
<td>14</td>
<td>8</td>
<td>2.0</td>
<td>(1.20, 3.42)</td>
</tr>
<tr>
<td>Out-of-Service Defect</td>
<td>7</td>
<td>4</td>
<td>1.9</td>
<td>(0.99, 3.80)</td>
</tr>
<tr>
<td>All Defects</td>
<td>21</td>
<td>12</td>
<td>2.0</td>
<td>(1.29, 3.07)</td>
</tr>
<tr>
<td>Tire Defects</td>
<td>310</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Violation Defect</td>
<td>14</td>
<td>11</td>
<td>1.2</td>
<td>(0.80, 1.86)</td>
</tr>
<tr>
<td>Out-of-Service Defect</td>
<td>2</td>
<td>5</td>
<td>0.5</td>
<td>(0.22, 1.21)</td>
</tr>
<tr>
<td>All Defects</td>
<td>16</td>
<td>16</td>
<td>1.0</td>
<td>(0.70, 1.53)</td>
</tr>
</tbody>
</table>

* Number of matched cases.

** Crude odds calculated using matched sets.

Note: Reference group is tractor-trailers without defects within each crash type.
Table 8
Adjusted Odds Ratios of Relative Risk of Crash Involvement for Tractor-Trailers with Equipment Defects

<table>
<thead>
<tr>
<th>Variables*</th>
<th>Adjusted Odds**</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equipment Defects</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Violation Defect</td>
<td>1.6*</td>
<td>(0.98, 2.46)</td>
</tr>
<tr>
<td>Out-of-Service</td>
<td>2.0*</td>
<td>(1.28, 3.11)</td>
</tr>
<tr>
<td>(None)</td>
<td>(1.0)</td>
<td></td>
</tr>
<tr>
<td>Adjusted For:</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hours Driving</strong></td>
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<tr>
<td>(0-2)</td>
<td>(1.0)</td>
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<tr>
<td>&gt;2-8</td>
<td>1.3</td>
<td>(0.83, 1.89)</td>
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<tr>
<td>&gt;8</td>
<td>1.7</td>
<td>(0.80, 3.45)</td>
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<tr>
<td><strong>Driver Age</strong></td>
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<tr>
<td>&lt;30</td>
<td>1.3</td>
<td>(0.82, 1.99)</td>
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<tr>
<td>(&gt;30)</td>
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<tr>
<td>Interstate</td>
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<tr>
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* Reference groups for odds ratios are shown in parentheses; the odds ratios are computed within each factor.
** Matched logistic regression; 214 cases in the adjusted model.
Table 9
Relative Risk of Crash Involvement for Tractor—Trailers With Brake, Steering, and Tire/Wheel Defects Adjusted for Other Factors*

<table>
<thead>
<tr>
<th>Type of Defect**</th>
<th>Percent with Defects</th>
<th>Adjusted Odds***</th>
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<td>Single Defects</td>
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<td>30</td>
<td>1.6</td>
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<td>5</td>
<td>3</td>
<td>3.6</td>
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<td>1</td>
<td>8.7</td>
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<tr>
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<td>6</td>
<td>7</td>
<td>1.2</td>
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<tr>
<td>Brake and Steering Defects</td>
<td>10</td>
<td>5</td>
<td>2.8</td>
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<tr>
<td>Steering and Tire/Wheel Defects</td>
<td>1</td>
<td>2</td>
<td>1.9</td>
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<td>Brake and Tire/Wheel Defects</td>
<td>10</td>
<td>6</td>
<td>3.1</td>
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<tr>
<td>Brake, Tire/Wheel Steering Defects</td>
<td>2</td>
<td>2</td>
<td>2.6</td>
</tr>
<tr>
<td>(No Defects)</td>
<td>31</td>
<td>44</td>
<td>(1.0)</td>
</tr>
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</table>

* Factors adjusted for include hours driving, driver age, carrier operation, carrier type, load, and power steering. For simplicity these odds ratios are omitted from table.

** Defect categories are mutually exclusive; percentage distribution is from unmatched data.

*** Matched logistic regression; 214 cases in the adjusted model; reference group for odds ratios is trucks with no defects (shown in parentheses) and is the same for each defect category.
Evaluation of Handling and Braking Characteristics of Heavy Vehicles

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Evaluation of handling and braking characteristics of heavy vehicles

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Abstract

In the years past, quite a number of relevant test procedures including appropriate criteria of description and evaluation respectively have been developed to objectively describe and assess handling and braking characteristics of passenger cars and passenger car-trailer combinations. These test procedures are basically applicable to commercial vehicles and combinations as well provided that either the starting conditions or the criteria of description are adapted to the special features of this particular class of vehicles.

With regard to the various design principles of commercial vehicles and the ever increasing advances of vehicle combinations ensuring optimum utilisation of cargo space i.e. single trucks or buses, truck-trailer combinations, semi-trailer combinations, articulated buses and short coupling truck combinations the handling characteristics of these vehicles are definitely more distinct from each other. The application of suitable test procedures one the one hand gives the feasibility to classify new vehicle combinations in comparison with existing designs and one the other side to optimize handling and braking characteristics in respect of increased traffic safety.

Within this paper test and measuring procedures generally applied to evaluate handling and braking characteristics of heavy commercial vehicles will be described. By measurements taken by the authors for a double-decker and a high-decker coach*, a 16-t truck**, two 7,5-t trucks** and a special type 38-t semi-trailer combination significant measuring variables are pointed out which can be used for evaluating the handling characteristics of the specific vehicle type.

* in charge of the German Federal Minister of Transport
** in charge of the German Federal Minister of Defense
Evaluation of Handling and Braking
Characteristics of Heavy Vehicles

TÜV Rheinland

Institute for Traffic Safety
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Cologne, F.R. Germany
EVALUATION OF HANDLING AND BRAKING CHARACTERISTICS OF HEAVY COMMERCIAL VEHICLES
Andreas Schindler, Klaus Rompe
TÜV Rheinland e.V. - Institute for Traffic Safety

1. INTRODUCTION

Commercial vehicles such as coaches or trucks represent an important economic factor in the Federal Republic of Germany. A great part of the transport service is produced by commercial vehicles, for example in 1987 approximately 14% of passenger transportation was serviced by coaches and about 50% of ton-kilometers were brought by trucks. Related to the covered distances this means that commercial vehicles with a proportion of 5% in the total number of registered motor vehicles meet about 11% of the whole annual kilometers of driving distance.

At the same time commercial vehicles are involved in about 17% of the accidents with casualties. With regard to an improvement in traffic safety the adaption of vehicles to the needs and capabilities of the drivers and the requirements of road traffic is of great importance. Hence to an increasing extent the handling characteristics of heavy commercial vehicles which play an important part in accident avoidance become a main field of development.

Sophisticated investigations of 182 commercial vehicle accidents conducted by the Medical University of Hannover in cooperation with the Technical University of Berlin allow some statements about the part of handling characteristics in accident events, Fig. 1. According to this the following order with regard to the relevance in accident events can be specified:
- braking performance 86% (locked wheel braking 45%)
- steering performance 39%
- directional control 21%

2. PRESENT STATE OF OBJECTIVE TEST PROCEDURES

The evaluation of handling characteristics of motor vehicles was mainly carried out by means of subjective assessments by experienced drivers or research engineers so far. But in recent years objective test procedures with comparable measuring and evaluation criteria have reached significance /1/.
In the years past quite a number of relevant test procedures including appropriate criteria of description and evaluation respectively have been developed to objectively describe and assess handling and braking characteristics of passenger cars and passenger car-trailer combinations. After comprehensive testing and discussion some of these test procedures were laid down as test standards in the national DIN working committee AA-I9 and the international ISO technical committee TC22/SC9. At present, however, commercial vehicles are not included in standardized test manoeuvers but these procedures are basically applicable to heavy vehicles and combinations as well provided that either the starting conditions or the criteria of evaluation and description are adapted to the special features of this particular class of vehicles.

At present state of knowledge the following six test procedures have proved their feasibility and expressiveness for the objective evaluation of handling and braking characteristics of heavy commercial vehicles in practical testing, Fig. 2:

1. Steady state cornering to determine the understeer/oversteer behaviour as a function of lateral acceleration or driving speed.
2. Step steering input to determine the promptness of vehicle response.
3. Frequency response measurement to determine the extent and promptness of vehicle response as a function of steering angle input.
4. Braking during steady state turning to determine yaw stability and steerability.
5. Straight line braking on a split adhesion surface (μ-split) to determine deceleration capability and driving stability.
6. Lane change to determine the steering effort and the effect of a lane change as an excitation function for yaw angle oscillations.

Within this paper some measurement results obtained by application of the test procedures mentioned above and suitable evaluation criteria will be presented. Most of the investigations referred to were conducted in commission by public authorities in particular the German Federal Minister of Transport.
3. MEASURING INSTRUMENTATION

In contrast to the subjective assessment of handling characteristics which generally is performed by experienced drivers with the help of rating charts the application of objective test procedures necessitates measuring devices to record the driver's input and the resulting vehicle response.

Fig. 3 shows a selection of the required measuring variables illustrated by the example of a truck-trailer combination. There is evidence that the standard variables referring to the towing vehicle such as steering angle, driving speed, lateral and longitudinal acceleration and yaw velocity are needed and so are corresponding variables referring to the further elements of the combination and the relative yaw angles at the different joints and couplings. Depending on the setting of the task and the specific vehicle type it may be necessary to measure and record additional variables e.g. separated for the driver's cabin and the platform.

In order to assess the dynamic capabilities of commercial vehicles up to limit performance depending on the specific vehicle type a rollover protection or a safety device to prevent jackknifing may be necessary to reduce the danger of accidents during the driving tests. The influence of these devices on the handling characteristics has to be determined in pre-tests.

4. TEST RESULTS

4.1 Steady state cornering

The test procedure steady state cornering is the method most frequently used to provide data on the steering tendency i.e. on the driving course as a function of steering angle and lateral acceleration. Furthermore this manoeuvre especially for commercial vehicles with a high centre of gravity gives a suitable approach to assess roll behaviour and dynamic roll resistance. The conditions for implementation as relating to passenger cars are specified in ISO Standard 4138.

Fig. 4 shows the steering wheel angle of a double-decker coach in two loading conditions (60% partial loading and gross vehicle weight) as a function of lateral acceleration /2/. In the lower lateral acceleration range up to approximately 2.2 m/s² corresponding to a driving speed of about 55 km/h the
bus exhibits practically no increase in steering wheel angle in both loading conditions, i.e. it shows a neutral to slightly oversteer behaviour. If the driving speed and hence the lateral acceleration increases the trailing axle which up to this point had also performed a steering action under the lateral force effect is fixed in straight line position. Consequently the steering wheel angle required to keep the course increases by more than 80°. In the higher lateral acceleration range, i.e. at driving speeds of more than 60 km/h, there is a clear understeer characteristic. The steering wheel angle requirement also increases with increasing lateral acceleration. This overall steering tendency clearly differs from the known and normal layout of cars and trucks and in dangerous situations the driver therefore certainly will have difficulties in controlling it.

4.2 Step steering input

The step steering input as applied to heavy commercial vehicles is comparable to that applied to passenger cars. The driving velocities range from 50 to 80 km/h with transient obtainable lateral accelerations of 2.5 to 5 m/s². The manoeuvre describes the vehicle response to a sudden steering input and simulates a driving situation which may occur in everyday traffic, e.g. an avoidance manoeuvre which requires a rapid steering input by the driver to make way for an obstacle.

The handling performance evaluated within this test procedure contains two essential qualities: on the one hand the magnitude of the vehicle response (gain) and the promptness of the response on the other hand. In addition to the yaw stability which becomes evident by the maximum values of yaw velocity, lateral acceleration and sideslip angle for the assessment of directional control of heavy commercial vehicles in particular the rollover resistance is of great importance. With regard to this a suitable criterion of evaluation is represented by the maximum values of roll angles measured during the overshoot of the vehicle response.

Fig. 5 illustrates these maximum roll angle values measured with two military 8-t trucks as function of the steady state lateral acceleration obtained after the steering input /3/. Both trucks were driven in un—loaden condition and with a special kind of radio cabin trunk. With increasing lateral acceleration the roll angles also increase, whilst the higher values and the greater relativ increase of roll overshoot angles of the loaded vehicles are not only influenced by the
changed centre of gravity height but also by the effective moments of inertia according to load contribution. Compared with the unloaded condition the limit of rollover stability characterized by the maximum lateral acceleration obtained decreases with cabin from 5.2 to 4.6 m/s². At this level of lateral acceleration the peak roll overswing angles reached with cabin exceed the values of the unloaded vehicles by 4 to 5°.

4.3 Sinusoidal steering

The sinusoidal steering input is used to determine the frequency response characteristics as the ratio of a periodic steering wheel input to vehicle reaction according to amplitude and phase at different steering frequencies. The procedure assumes that the transfer characteristics of the vehicle can be described in a linear way with good approximation. The frequency response of a linear dynamic system is a function which describes the amplitude ratio of output and input signals and the phase lag between both signals in steady state condition depending on frequency. In comparison to other procedures specified in document N 280 of ISO/TC22/SC9 this method provides the most reliable results in frequency domain.

Measurements of amplitude frequency characteristics of the yaw velocity for three coaches, a standard coach (A), a high-decker coach (B) and a double-decker coach (C) with permissable total weight each are illustrated in Fig. 6 /2/. The actual tests started with a steering frequency of 0.2 Hz which was gradually increased up to 1.8 Hz. The amplitude of the steering wheel angle was previously defined during steady state cornering with a driving speed of 80 km/h so that a lateral acceleration of 3 m/s² was reached.

In order to assess the frequency response functions the examination primarily concentrates on the relative changes of the variables in relation to the 'quasi-steady state' initial value obtained at 0.2 Hz. To ensure that the yaw reaction to steering movements is not too adverse the increase in yaw velocity amplitude should not be too high in the frequency range from 0.2 Hz to approximately 1.0 Hz. At the same time a resonance point in yaw response which in this frequency range is shifted to higher frequencies can be assessed more favourable in most cases than values distinctly below 1.0 Hz.
The amplitude frequency characteristics of yaw velocity show for all three coaches a continuous decline in yaw response without any distinct resonance point as it usually can be detected with passenger cars and trucks respectively. The large yaw inertia inherent in these vehicles finds expression in this phenomenon. With reference to the standard coach the phase angles of yaw velocity indicate that the temporal build-up of the vehicle reaction in the examined frequency range occurs later than in the high-decker and double-decker coach and must therefore be assessed as less favourable.

4.4 Braking during steady state turning

The test procedure of braking during steady state turning was designed to yield information about the extent to which a vehicle's steering behaviour is influenced by the simultaneous acting of braking forces. The criteria for evaluation are measuring variables describing the capacity to keep the course, yaw stability and steerability with distinct decelerations. For heavy commercial vehicles the international standard DIN/ISO 7975 provided for passenger cars has to be adapted especially in terms of starting conditions. The reasons are primarily the lower physically obtainable lateral acceleration during cornering and the comparatively long time required until deceleration sets in /4,5/.

The evaluation functions are established by deriving reference values from the time functions measured in single tests. Such reference values are synchronous values obtained from the single tests e.g. 1.5 s after brake application over the respective deceleration. For minor variations in the starting conditions to be equalized yaw velocity and lateral acceleration are related to the initial values of the steady state driving condition and the variation of the sideslip angle as compared with the initial state is plotted. Besides a reference curve is used for evaluation purposes. The underlying principle is that a vehicle will continue to travel exactly along the initial radius even after brake application and that deceleration and sideslip angle will remain constant during the braking manoeuvre.

Fig. 7 illustrates the evaluation functions of sideslip angle, yaw velocity and lateral acceleration measured on the platform of a 8-t truck under partial load and maximum permissible weight. The values were determined in test series on a radius of 100 m and an initial lateral acceleration of 3 m/s². With inclining deceleration the characteristic functions of related yaw velo-
city and lateral acceleration show increasingly higher values than the affiliated reference curves do. The maximum values can be observed at a mean deceleration of about 3 m/s² in loaded condition and at 4 m/s² with partial weight. Hence it follows that with increasing deceleration up to the point the rear wheel on the inside of the curve locks the vehicle goes off the course towards the inside of the bend. Caused by the large yaw inertia the maximum tendency of turning inwards is comparatively slighter with the loaded truck. With further increasing deceleration the vehicle regains the capacity to keep the course because of the intensive adhesion utilization at the front wheels.

Since the absolute values of related yaw velocity and difference of sideslip angle obtained in both loading conditions do not show any lack of yaw stability the braking performance during cornering has to be assessed more favourable for the truck with partial load. This applies as well on the basis of the higher obtainable maximal deceleration as relating to the capacity to keep the course in the deceleration range up to 3.5 m/s² usually engaged by average drivers.

4.5 Braking on a μ-slit surface

Braking manoeuvres on roads where the left and right wheels are on pavement sections with different adhesion characteristics represent a particularly critical driving situation specifically in relation to holding the course and driving stability. As result of the different adhesion properties of the pavement different braking forces can be transmitted by the left and right vehicle wheels. This leads to a corresponding yaw response and a course deviation towards the vehicle side with the higher road adhesion. In the case of full braking vehicles without antilock brake system will start to spin very rapidly and change to an unstable driving condition.

Usually the starting condition for the test procedure is straight line driving with driving speeds ranging from 60 km/h to 80 km/h. Having reached a steady state driving condition the vehicle is decelerated by applying different but for the single tests constant brake pressures. The application of this test manoeuvre requires special test tracks with lanes of different adhesion properties, e.g. an asphalt/wet blue basalt surface.
The criteria of evaluation are measuring variables which describe the deceleration capacity, yaw stability and especially for heavy commercial vehicles rollover stability. Fig. 8 illustrates the maximum values of yaw velocity determined in the period of 1 s after brake application for the different coaches previously mentioned. These values obtained under full braking condition with the steering wheel fixed in straight line position clearly demonstrate the benefit of an antilock brake system for commercial vehicles. While the conventionally braked standard coach A with locked wheels violently skids in the direction of the high adhesion surface the coaches B and C which are equipped with an antilock system maintain good directional stability and can easily be controlled even by unexperienced drivers.

4.6 Lane change

This test procedure is applied to serve a dual purpose in the evaluation of handling characteristics of heavy commercial vehicles:

1. Evaluation of transient steering behaviour
The driving course chosen usually corresponds to the ISO lane change manoeuvre which is to be understood as a lane displacement of 3.5 m over a distance of 30 m. With this the evaluation will cover especially the steering activity, i.e. the amount of required steering movements to be made by the driver to first keep the lane and than to stabilize the vehicle.

2. Evaluation of the damping behaviour of the combined elements
In this test which is based on a course similar to the ISO lane change, e.g. in the form of a single or dual lane change, the manoeuvre will mainly serve to excite the combination’s oscillation. The aim of the test procedure is to determine the damping of the yaw angles and the oscillation paths at the end of the trailer.

The measured values will therefore be recorded only after the lane has been changed and the vehicle is driven straight ahead again. A short steering angle impuls as applied for passenger car-trailer combinations will not suffice to generate an adequate oscillation energy in commercial vehicles.

Fig. 9 shows the position of the elements of a special type 40-t semitrailer combination after having passed a single lane displacement of 3 m over a distance of 40 m on a wet hardly skidding surface at 1 s intervals. At a driving speed of about 73 km/h the vehicle combination proves a good oscillatory stability with relatively
small articulation angles. The oscillation paths at the end of the second semitrailer range in the lower region of values obtained with tractor-trailer combinations which under comparable conditions reach from 1 m to 4 m.

5. CONCLUSIONS

As illustrated by means of a few examples the test procedures applied to determine the handling and braking characteristics of passenger cars are basically applicable to heavy commercial vehicles as well. In doing so one should bear in mind that there is a need for adapting either the starting conditions or the criteria of evaluation accordingly.

With regard to the variety of commercial vehicle configurations it will be necessary in some cases to confine to comparative tests in order to evaluate basic concepts and the effects of single parameters respectively. For this the test procedures presented within this paper form expressive facilities especially against the background of a further improvement in driving safety of commercial vehicles. Consequently it seems necessary and useful to continue with the work in advancement and application of test procedures for the evaluation of handling characteristics of heavy commercial vehicles.
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### Handling of commercial vehicles in case of accidents

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ref.: UFO MHH / TUB / BAST 1985

**Figure 1:** Handling performance of commercial vehicles related to accidents
Figure 2: Objective test procedures for the evaluation of handling characteristics of commercial vehicles.
Figure 3: Commercial vehicles measuring variables

Figure 4: Steering wheel angle as function of lateral acceleration for a double-decker coach under 60% partial load and maximum permissible weight
Figure 5: Maximum roll angles in transient response as function of steady state lateral acceleration for step steering input under test weight and cabin loading condition.

\[ v_x = 72 \text{ km/h} \]

Dry road

--- Truck A
--- Truck B

\( \phi_2 \) (deg)

lateral acceleration \( a_{y,\text{stat}} \) (m/s²)
Figure 6: Gain and phase angle function of yaw velocity for three coaches under maximum permissible weight loading condition.
Figure 7: Reference functions for a 8-t truck under partial load and maximum permissible weight for braking during steady state turning on a dry road.
Braking on $\mu$-split

$$v_X = 60 \text{ km/h}$$

**Figure 8:** Maximum yaw velocity in a time interval of 1 s after brake application
Figure 9: Positions after an extreme lane change of the elements of a specific type semitrailer under maximum permissible weight
Heavy Vehicle Braking - U S vs Europe

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Vehicle Research and Test Center
National Highway Traffic Safety Administration
U S A

presented by

Robert E Spicher
Transportation Research Board (TRB)
U S A
Heavy Vehicle Braking Philosophies - U.S. vs. Europe

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National Highway Traffic Safety Administration

Abstract

Differences in regulations and design philosophies have brought about the development of significantly different hardware in the braking systems of U.S. and European heavy vehicles. In the service braking system, for example, European heavy vehicles generally have larger front brakes than their U.S. counterparts, and they are usually equipped with load-sensing brake proportioning valves (not used on U.S. vehicles). Emergency brake systems and parking brake systems are also different. This paper discusses those differences that have a significant impact on safety-related performance and presents the results of recent tests that were run to compare the braking performance of a typical U.S. five-axle tractor semitrailer combination to a typical European vehicle of the same basic size, weight and axle configuration in various simulated accident avoidance maneuvers.

Introduction

Braking systems on heavy vehicles in the United States and Europe are very different. This is primarily due to differences in design philosophies and differences in regulations. There is little similarity between FMVSS Nos.105 and 121, the U.S. braking system regulations, and ECE Regulation 13 and EEC Directive 71/320, the European braking system regulations. A vehicle that meets the U.S. regulations would probably not meet the ECE/EEC regulations and vice versa.

The purpose of this paper is to discuss some of the major differences that exist in the braking systems of the heavy vehicles produced on both continents and to point out the reasons for these differences from a regulatory and design philosophy point of view. The paper will also present and discuss the results of braking performance tests that were run to compare a typical U.S. combination vehicle to a typical European combination vehicle.

No attempt will be made to take the comparison to the "nuts and bolts" level. There are many hardware differences which do not affect braking performance to any measurable degree, and these are not of particular interest here. In addition, those hardware differences that affect durability, reliability and maintainability, although obviously important, will not be discussed here; the primary focus will be on those differences that affect crash avoidance capability.
Summary and Conclusions

Braking systems on U.S. and European heavy vehicles are very different and these differences are apparent in the service, emergency and parking portions of the systems. These hardware differences are due to disparities in the regulations and in the design philosophies on both continents. The most significant point of divergence is the manner in which braking forces are distributed in the service brake system among the various axles because this can impact performance in the most common accident avoidance situations.

European heavy vehicles typically utilize more braking at the steering axle (although this only applies to heavy vehicles with air brakes and not those with hydraulic brakes), and they utilize load-sensing proportioning valves that are not found on any U.S. heavy vehicles. Calculations and simplified vehicle dynamics theory indicate that European vehicles should exhibit superior braking efficiency under all loading and road surface conditions primarily because their brake forces are more closely balanced to their dynamic axle loads. Recent experiments comparing a typical European combination and a typical U.S. combination indicate that this is not necessarily the case, however.

Braking tests conducted at various trailer loads (as well as with bobtail tractors) in various simulated accident avoidance maneuvers indicate that the U.S. vehicle could outperform the European vehicle in a number of cases. When the U.S. vehicle was not equipped with an automatic front-axle limiting valve (these devices are an optional equipment item and are installed on many U.S. vehicles), the U.S. vehicle outperformed or was within ten percent of the performance of the European vehicle in 13 of the 24 cases evaluated. With this limiting valve, however, this "close to or better than" performance condition was achieved by the U.S. vehicle in only 6 of the 24 cases evaluated.

The European tractor significantly outperformed the U.S. tractor in all bobtail tests unless the U.S. tractor was equipped with a bobtail proportioning system (another brake equipment option available on U.S. vehicles). With such a device the U.S. tractor was able to equal or exceed the performance of the European tractor in all cases except the high-mu (dry road) case. Here the European tractor stopped 25 percent shorter primarily due to its larger front brakes (the U.S. tractor could not lock its wheels on the dry surface).

Differences between "theory" and experiment may be explained by two factors. First, the load-sensing valves did not perform in accordance with the simplified way in which they were "modeled" in the calculations and, second, the definition of limit performance used in the calculations did not agree with the "real" limit in the tests. The calculations assumed that the limit would be reached (i.e., loss of control would occur) when only one axle of the tandem axles locked. In the tests it was found that both axles needed to be locked before control loss occurred.

The primary difference in the performance of the emergency brake systems on U.S. and European powered vehicles with air brakes is the fact that U.S. vehicles cannot continue to operate indefinitely with a failure in the pneumatic system. After some number of stops the parking brakes will apply. With a European vehicle, intact reservoirs can be replenished and partial system performance can be maintained indefinitely. European trailers employ relay-emergency valves for emergency braking capability (these were used on U.S.
vehicles prior to FMVSS No. 121), whereas U.S. trailers utilize their parking rakes (usually spring brakes) to serve this function.

Although parking brake systems on powered vehicles are essentially the same between the U.S. and Europe, trailer parking brake systems are significantly different. European trailers employ a hand crank mechanism that must be activated by the driver after exiting the vehicle and standing beside the trailer to operate it. U.S. trailers use spring brakes (or other approved devices) that are activated via a control knob in the tractor.

References


1.0 INTRODUCTION

Braking systems on heavy vehicles in the United States and Europe are very different. This is primarily due to differences in design philosophies and differences in regulations. Heavy vehicles produced for the U.S. market typically do not meet European brake regulations and vice versa. The purpose of this paper is to discuss some of the major differences that exist in the braking systems and to point out the reasons for these differences from a regulatory and design philosophy point of view. The paper will also present and discuss the results of braking performance tests that were run to compare a U.S. combination vehicle to a European combination vehicle. Although broad generalizations cannot be made as a result of tests on only one combination vehicle from the U.S. and one combination vehicle from Europe, it is possible to gain insights on the effect of the basic hardware differences on performance.

No attempt will be made to take the comparison to the "nuts and bolts" level. There are many hardware differences which do not affect braking performance to any measurable degree, and these are not of particular interest here. In addition, those hardware differences that affect durability, reliability and maintainability, although obviously important, will not be discussed here; the primary focus will be on those differences that affect crash avoidance capability.

2.0 SERVICE BRAKE SYSTEMS

2.1 Brake Force Distribution

The most significant difference between U.S. and European heavy vehicles related to braking performance in crash avoidance situations is the manner in which braking forces are distributed in the service brake system among the various axles. The European regulations contain very specific requirements for brake force distribution. Manufacturers must provide calculations that show the distribution of braking forces over a broad range of decelerations, and these forces must fall within specified bands. These brake force distribution requirements must be met at all states of vehicle loading.

The underlying philosophy for these requirements is based on the vehicle dynamics axiom which says that brake forces at the axles should be balanced as closely as possible to the dynamic normal forces at the axles so as to produce high levels of braking
efficiency, regardless of load or surface coefficient of friction. Braking efficiency here refers to the ability of the vehicle to achieve a relatively high deceleration (considering the limitations imposed by the surface friction level) before wheel lockup and the corresponding loss of control occurs.

The European brake force distribution requirements, contained in ECE Regulation 13 and EEC Directive 71/320, are calculation based and do not specify that a test be run to verify the results, although presumably a test of some sort is necessary to develop the performance data for the brakes needed in the calculations. It is not clear in the European regulations how a manufacturer arrives at these "brake factors" and it would appear that many different methods are used.

In order to meet the European requirements, heavy vehicles must have relatively large brakes on the steering (front) axles and load-sensing proportioning valves on drive (rear) axles and trailer axles. The large front brakes are necessary to match the high front axle loads that occur as a result of weight transfer during braking; load-sensing valves must be used to reduce pressure (and thus braking) at the drive and trailer axles when the vehicle is unloaded or partially loaded.

The U.S. regulations do not specify brake force distribution directly. FMVSS No. 105, the U.S. regulation for hydraulic brake systems, does contain stopping distance requirements for service brake systems on light vehicles on dry pavement and these requirements necessitate a reasonably good front-to-rear brake balance, however, similar requirements do not exist for heavy hydraulically braked vehicles. FMVSS No. 105 does contain emergency (failed-system) stopping performance requirements for heavy vehicles which can not be met unless the vehicle has both front and rear brakes, however, these requirements permit a fairly wide range of braking force distributions.

Even though FMVSS No. 105 does not require a specific brake balance or minimum level of efficiency, heavy hydraulically braked vehicles produced in the U.S. generally have reasonably good brake balance. Although they do not use the load-sensing valves found on similar vehicles in Europe, they typically have relatively large front brakes. It is not unusual, for example, for such a vehicle to have 50 percent of its braking on the front axle when only 30 percent of its static weight is on the front axle. Most U.S. vehicles in this category are equipped with four-wheel disc brakes, and it is common practice to use the same brake on both front and rear axles. (Although hydraulic drum brakes are more common on this class of vehicle in Europe, use of similar brakes on front and rear axles is a common practice there as well).

The remainder of this paper will focus on air brake systems since that is where the bulk of the differences exist between U.S. and European vehicles.

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FMVSS No. 121, the U.S. regulation for air brake systems, does not currently contain any stopping distance requirements (they were struck down by the U.S. Courts in 1978) but does contain other requirements that can influence brake force distribution. First of all, FMVSS No. 121 requires that vehicles have brakes on all axles. In addition, brake power (fade) and recovery requirements contained in the standard are specified in terms of gross axle weight ratings (GAWR). Individual brakes must be tested on an inertia dynamometer with a "load" (inertia) equivalent to the GAWR of the axle on which they are installed on the vehicle.

In addition to the brake fade and recovery requirements which apply to all air braked vehicles, trailers are required by FMVSS No. 121 to have brakes sized in such a way as to provide a minimum retarding force directly related to the GAWR of the axle on which they are installed. Although both the fade/recovery and trailer retarding force requirements are based on GAWRs, they specify only minimum braking forces at axles and as such, do not dictate a specific brake force distribution.

A recent study (Reference 1) conducted by the Vehicle Research and Test Center (VRTC) measured the brake force distribution on 15 air-braked U.S. combination vehicles to determine how brake force distribution compared to axle ratings. The results indicated that although the distribution of braking between drive and trailer axles was generally aligned with the distribution of the corresponding GAWRs, all of the vehicles were under-braked on their steering axles (i.e., the steering axle brake force percentage was less than that indicated by the front axle GAWR percentage).

Some of the low levels of front axle braking force found on the U.S. vehicles in this study can be traced to the use of automatic front axle limiting valves (ALVs). These devices are found on about half of all U.S. tractors and trucks with air brakes. Although most manufacturers no longer offer them as standard equipment, many users specify (and obtain) them when they order vehicles. Such valves reduce the front brake pressure by 50 percent until approximately 40 percent of full control pressure has been applied at which point they begin to blend back to a 1:1 (no limiting) mode. By about 60 percent of full control pressure, they no longer limit brake pressure on the front axle.

Even without ALVs, the U.S. vehicles in the VRTC study still had somewhat less braking on their steering axles than GAWRs would dictate if following the practice of balancing brakes in accordance with axle ratings. This practice of balancing brakes in accordance with GAWRs is considered generally to be the U.S. design philosophy, although it is obvious from the measurements on the 15 combinations that it is not strictly adhered to, particularly on front brakes.

In order to compare the effectiveness of the brakes on the various axles in a U.S. and a European heavy vehicle, VRTC conducted brake force distribution tests in accordance with SAE Recommended Practice J1505 on a typical U.S. five-axle tractor semitrailer (6x4
S2) and a similarly configured European combination that meets ECE/EEC regulations. Reference 2 describes these tests and the test vehicles in detail. (This report actually describes a much broader program where the braking performance of the two combinations was studied in detail; the results of the test program will be referred to throughout the remainder of this paper.)

Figure 1 gives the results of the brake effectiveness comparison. Brake effectiveness is defined here as the slope of the brake force (total on the axle or tandem axle set) versus brake chamber pressure relationship. Linear regression analysis was utilized on the SAE J1505 results to determine effectiveness. Brake chamber pressure was used in this analysis instead of control line pressure (the parameter normally used with J1505 data) because it provides a direct input-output relationship for the foundation brake assemblies and does not include the effect of the load-sensing proportioning valves, which modify control line pressure. The relationship of brake force to control pressure is usually the important parameter because it establishes brake force distribution and braking efficiency; however, the purpose of these tests was to compare only the effectiveness of the foundation brake assemblies and not the entire air brake systems.

![Brake Force vs. Chamber Pressure Graph](image)

**FIGURE 1.** Comparison of the effectiveness of the foundation brakes on axles of a U.S. combination and a European combination.

It can be seen in Figure 1 that the European vehicle has about 60 percent more brake force on the front axle than does the U.S. vehicle. On the other hand, the European vehicle has about 35 percent less force on the drive tandem and about 25 percent less force on the trailer tandem. Overall the European combination has about a 20 percent lower total brake force. It should be noted that brake forces were measured only up to 60 psi, and as such the
effectiveness values might have been slightly different if the full pressure range had been covered (i.e., up to about 100 psi). It also should be mentioned that although the U.S. vehicle brake effectiveness appears to be quite typical based on tests of other U.S. combinations (Reference 1) such data is not available on European vehicles and it is not known how representative the data here is of the European fleet. Nevertheless, the size of the brakes (drum sizes, chamber sizes, slack lengths, etc.) on the European vehicle tested here are not atypical with respect to the rest of the European fleet.

If Figure 1 were to be reconstructed using control line pressure to calculate effectiveness, the values should be the same for the fully loaded case but would be considerably different for the empty case. In the empty case, the load-sensing valves, which reduce braking at the drive and trailer axles on the European combination, would significantly reduce the effectiveness of the brakes on these axles. In the case of the U.S. empty vehicle, if it were equipped with an ALV, the front brake effectiveness would be reduced by approximately 50 percent (up to about 40 psi).

2.2 Braking Efficiency

Brake force distribution has a significant effect on braking efficiency or the ability of the braking system to utilize available tire/road friction before wheel lockup and control loss occur. "Perfect" brake balance (100 percent efficiency) occurs when brake forces on the wheels match the normal forces on the wheels. In such a case, all wheels on the vehicle would lock up at the same brake system input level (pedal force or control-line pressure).

Although the underlying philosophy behind the ECE/EEC brake force distribution requirements is to achieve high levels of braking efficiency under all load and road surface conditions, these regulations do not require "perfect" brake balance; considerable tolerance is allowed, and efficiencies as low as 50 percent are permitted under some conditions. The highest efficiency required by the European regulations for heavy vehicles is only 79 percent.

Since the U.S. regulations do not specify brake force distribution or efficiency for heavy vehicles, they permit considerable latitude in brake balancing. As was mentioned earlier, the U.S. "design philosophy" for air brake systems is generally to balance brake forces in accordance with GAWRs. With this distribution, reasonably high levels of efficiency can be achieved with laden vehicles but unladen vehicle efficiency is relatively poor. This is because the lightly loaded axles are overly effective and tend to lock the wheels prematurely (i.e., at a relatively low deceleration compared to what could be achieved on the particular surface if brakes were well balanced).
2.3 Calculated Efficiency

The University of Michigan Transportation Research Institute (UMTRI) recently conducted a study (Reference 3) comparing the dynamic performance of a European combination and a U.S. combination. This study was analytical in nature (i.e., it utilized computerized models to predict dynamic turning and braking behavior), but it did use vehicle parametric data that was experimentally determined. For the braking portion of the study UMTRI utilized the brake effectiveness data and the load-sensing valve load-pressure characteristics measured by VRTC in the experimental study of braking performance of a U.S. and a European combination (Reference 2). UMTRI calculated the braking efficiency of the two different combinations at a 0.4g deceleration as follows:

<table>
<thead>
<tr>
<th></th>
<th>Calculated Efficiency, %</th>
<th>European Vehicle Advantage, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laden</td>
<td>U.S. 71</td>
<td>European 87</td>
</tr>
<tr>
<td>Unladen</td>
<td>U.S. 53</td>
<td>European 80</td>
</tr>
</tbody>
</table>

These data indicate that the European combination exhibits superior performance at both loading conditions at a 0.4g deceleration. Reference 3 shows the superior performance to exist at other decelerations as well. The European combination shows a particularly large advantage (51%) in the unladen state primarily due to the effect of the load-sensing valves. In these calculations the U.S. tractor did not have an ALV; such a valve would lower the unladen efficiency. The ALV would not affect the laden case, however, because the ALV would not be limiting pressure to the front axle at the high control-line pressures necessary to stop the laden vehicle.

The braking efficiency calculations indicate that the European combination should be much less likely to lose control in accident maneuvers and should be able to stop in much shorter distances under all possible conditions of loading and road surface friction.

2.4 Experimentally Determined Performance

In order to compare the results of the calculations to the actual on-road performance of the two different combinations, the results of the VRTC braking tests (Reference 2) will be reviewed next. Although this test program is covered in detail in Reference 2, a brief synopsis of the test program will be given here to provide some background before proceeding to the discussion of the test results.

As mentioned earlier, the test vehicles were three-axle tractor/two-axle semitrailer combinations typical of vehicles sold on the respective continents. Both vehicles had the same basic dimensions, the same test weights (the tare weight of the European vehicle was a little higher, however) and the same brand/size/tread...
design tires. Both combinations were equipped with new OE brake linings which were burnished with 1000 stops before beginning the performance tests.

Although two axle tractors are more common in Europe than three-axle models, the three-axle European tractor was selected because it matched the most common U.S. combination. Since the intent of this program was to compare braking systems only, it was desirable to eliminate as many extraneous variables as possible. It was not possible to match the suspensions on the two combinations because of hardware availability and there were some basic differences in the tandem suspensions and their interaxle load transfer characteristics (the U.S. tractor suspensions exhibited more interaxle load transfer during braking). It was not felt that the suspension differences had a significant effect on the braking results, however, because braking performance limits (i.e., loss of control) usually were reached only when lockup of all wheels on the tandems occurred. This was true on both combinations.

Several different types of braking maneuvers were performed with the combinations and tractors alone (bobtail). The combinations were tested with empty trailers, half loaded trailers and fully loaded trailers. Straight line stops, stops while turning and stops while changing lanes were utilized as the test maneuvers. The straight line stops were performed on surfaces with uniform coefficients of friction including dry concrete, wet polished concrete and wet Jennite-coated asphalt* The coefficients of friction for these surfaces, measured in accordance with the ASTM E274 "skid trailer" procedure, were 0.8, 0.3 and 0.2 respectively. The straight-line stops were also run on a split coefficient of friction surface (left to right) utilizing the wet Jennite and wet asphalt (0.65 coefficient of friction). The curve and lane change maneuvers were run only on the wet Jennite surface.

The same test driver performed all of the tests. He tested one vehicle at one particular test condition, then switched to the other vehicle and conducted the same tests on it. In the straight-line stops on the uniform surfaces he attempted to make the shortest possible stop without locking more than one wheel per axle or two wheels per tandem. In all other tests he attempted to make the shortest possible stop without leaving the 12-foot-wide test lane (i.e., without losing control). The wheel lock criterion was utilized in the straight-line stops on uniform surfaces instead of the loss-of-control criteria because in these stops there was essentially no side force on the vehicle. The test track has no side slope. The wheel lock criterion thus provides an indication of the braking rate at which the loss of control would occur on actual roads where side forces due to road crown, etc. are present. In the case of the stops with turning or the stops on the split coefficient of friction surface, the lockup criterion was unnecessary. If the driver locks the wheels, the vehicle will leave the test lane. Testing previously conducted, as well as the testing conducted here, indicates that lockup of all wheels on an axle (or pair of axles in the case of a tandem) is necessary for control loss in the test maneuvers commonly utilized.

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the other four cases the difference was relatively small (i.e., less than ten percent). In the straight-line stops on wet polished concrete and in the curve on wet Jennite, premature lockup of the steering axle on the European combination resulted in its taking 29 and 23 percent longer, respectively, to stop in a stable fashion than the U.S. combination.

In the bobtail tests, the European tractor was superior by a significant amount (19-35 percent) in all of the maneuvers. Premature lockup of the drive axles on the U.S. tractor made it difficult for the driver to stop without spinning out.

With the empty trailer the European combination generally performed better than its U.S. counterpart, particularly on the high coefficient of friction (dry) surface where the stopping distance was shorter by 33 percent. Differences in performance on the wet surfaces were smaller, and, in fact, on the curve the U.S. combination stopped a little shorter.

When the trailer was one-half loaded (weight distribution was uniform in this condition) the differences between the combinations were relatively small under most conditions. The biggest difference occurred on dry pavement, where the European combination stopped 13 percent shorter.

Two phenomena relative to the performance of the load-sensing proportioning valves on the European combination were observed during the tests and are worth noting. First of all, it was found that during stops the load-sensing valves on both tractor and trailer tandems tended to "cycle" and dump air, reducing the available reservoir pressure. In stops requiring high pressures (such as loaded stops on dry pavement) a reduction in total system air pressure prevented the brakes from developing full torque output (and full stopping capability). Second, it was found that during turns the trailer's load-sensing valve reduced pressure to the trailer brake. Apparently the valve was affected by lateral acceleration (and the resulting roll of the sprung mass). These factors are important to mention because they were not taken into account in the braking efficiency calculations discussed above.

It is clear at this point that the experimental results do not agree with the calculations. The calculations indicate that the European combination should be superior in the fully loaded and unloaded trailer cases (calculations were not made for the bobtail and half-load cases) at all surface friction levels. The European combination should have been significantly better with the unloaded trailer, according to the calculations. The test results, on the other hand, show that the differences are relatively small with the unloaded trailer except in the dry road tests, where the European combination did stop 33 percent shorter. In addition, the experimental data show that in the fully loaded case, the U.S. combination stops significantly shorter than the European combination in several maneuvers. In the remaining loaded cases the differences between the combinations is small.
For each test condition the driver made six stops. The best of these stops was used to quantify the vehicle's performance under that particular test condition. This provides a good measure of the vehicle's limit braking performance by minimizing driver performance influence. Best-stop stopping distance in these test maneuvers, therefore, serves as a surrogate measure of braking efficiency.

Figure 2 provides a summary of the results of the experimental comparison. It shows the percent difference in best-stop stopping distance for the various maneuvers. For each maneuver, results are given for each of the four loading conditions. Values above the zero datum indicate that the European vehicle is superior. In calculating percent improvement the U.S. results were used as the basis (i.e., the denominator) in the calculation. Although the U.S. combination was tested both with and without the ALV operational, the results in Figure 2 are for the case without the ALV.

FIGURE 2. Comparison of performance in various braking maneuvers (U.S. vehicle w/o ALV).

It can be seen in Figure 2 that the largest differences occurred for the fully loaded combinations and the bobtail tractors. In the fully loaded condition, the U.S. combination significantly outperformed the European combination in two of the six cases; in

*Jennite™ is a brand of tar emulsion sealer commonly employed to protect asphalt surfaces.
Although the calculations do take the basic properties of the load-sensing valves into account, they do not allow for the cycling and "dumping" of air and the sensitivity to lateral acceleration described above. It is possible that some of the differences between the experimental results and the calculations can be traced to this factor. Another possible factor relates to the way in which braking efficiency is defined. The definition used in the UMTRI study assumes that the limit occurs when lockup of the wheels on only one axle occurs. In the tests, however, it was found that loss of control did not occur until wheels on an entire tandem locked up. The U.S. combination, because of its suspension design and its higher level of interaxle weight transfer, was penalized in the calculations but actually performed better than expected in the full-scale vehicle tests.

2.5 Automatic Front Axle Limiting Valves

Most U.S. tractors can be purchased with ALVs, and a large number of vehicles are built that way. When the tests in Reference 2 were performed the U.S. combination was run both with and without such a valve operational so that it would be possible to make the comparison both ways. Figure 3 shows the result. The format for Figure 3 is identical to that of Figure 2.

![FIGURE 3. Comparison of performance in various braking maneuvers (U.S. vehicle w/ ALV).](image)

By comparing Figure 3 to Figure 2 it can be seen that the performance of the U.S. combination degrades with the ALV, increasing the advantage for the European combination in almost all of the cases. With the ALV, the U.S. vehicle tends to lock its rear wheels at a lower deceleration than without it. The bobtail
mode shows the greatest degradation; stopping distance increased by about 30 percent in three of the maneuvers and between five and twenty percent in the other three.

2.6 Bobtail Brake Proportioning Systems

It can be seen in both Figures 2 and 3 that the largest difference between the U.S. and European combinations occurs in the bobtail tractor mode. Several U.S. vehicle manufacturers are now offering bobtail proportioning systems. These systems sense when the trailer is disconnected (by sensing pressure in the tractor air line that provides supply air to the trailer) and proportion air to the drive-axle brakes whenever the tractor is operating bobtail. These systems are simple, low-cost and require no adjustment.

In order to determine how a U.S. tractor with such a device would perform compared to a European tractor with load-sensing proportioning, the vehicles described above were retested with the U.S. tractor equipped with a bobtail proportioning system. The results are shown in Figure 4. This figure is in the same format as Figures 2 and 3 and actually repeats the data for the empty, half-load and full-load cases that are shown in Figure 2 (i.e., U.S. combination with no ALV). It is presented this way not only to compare the bobtail performance but to show how a U.S. vehicle, configured with a production braking system set up for the best possible performance, would compare to a European vehicle from an overall standpoint.

FIGURE 4. Comparison of performance in various braking maneuvers (U.S. vehicle w/ bobtail proportioning).
It can be seen in Figure 4 that the U.S. tractor outperformed the European tractor in four of the six bobtail cases. The only bobtail case where the European vehicle performed better was on the dry surface, where it stopped about 25 percent shorter than the U.S. tractor. The higher-output front brakes on the European tractor probably caused this difference. Although the European tractor could lock its front wheels on the dry surface, the U.S. tractor could not.

Considering all of the maneuvers and all of the loading conditions evaluated in this test program, Figure 4 indicates that if the U.S. tractor were equipped with bobtail proportioning and without an ALV, its performance in most cases would be either better than or within about ten percent of the performance of the European vehicle. The European vehicle was still significantly better both bobtail and with an empty trailer on dry pavement, however, due to the larger brakes on the steering axle.

3.0 EMERGENCY BRAKE SYSTEMS

3.1 Powered Vehicles

The ECE/EEC braking regulations specify that heavy vehicles with single failures in their pneumatic systems must be able to achieve a deceleration that is 50 percent of the level required with fully intact service brakes and this level of performance must be maintained indefinitely (i.e. if test stops are repeated). FMVSS No. 105 specifies a similar level of performance but does not state that it be maintained indefinitely. In fact, only one stop needs to be made to meet the requirements. Originally FMVSS No. 121 had emergency system requirements similar to FMVSS No. 105, but with the withdrawal of the stopping distance requirements in response to the Ninth Circuit Court decision, emergency system performance became unspecified in the U.S. air brake standard.

The obvious major difference between the U.S. and European standards for emergency brake systems is the fact that Europe requires performance to be maintained indefinitely whereas the U.S. does not. This difference has not really had an effect on the design of hydraulically braked vehicles because they (both U.S. and European vehicles) employ "closed" subsystems, which inherently meet the indefinite provision.

The emergency brake system for air braked vehicles (which utilize "open" type subsystems) are significantly different between U.S. and European vehicles. U.S. vehicles are plumbed in such a way that if a failure occurs in one of the subsystems, the remaining subsystem cannot be replenished; supply air from the compressor is expelled through the failed system and is not available to "recharge" the intact subsystem. With a pneumatic failure in a U.S. vehicle, pressure in the intact subsystem will continue to drop each time a stop is made until eventually the parking brakes apply, immobilizing the vehicle.
In European vehicles, the subsystems are each isolated with pressure protection valves (as opposed to the simple two way check valves used on U.S. vehicles). These valves, which do not open until a preset pressure is reached, allow the unfailed (intact) subsystem to be recharged up to about 60 percent of full pressure. Replenishment above this level is not possible because the pressure protection valve on the failed subsystem opens, allowing air to escape via the failure.

Being able to maintain a constant level of performance after a failure is a "mixed blessing"; it can be argued that allowing a vehicle to continue on its way with a failure and significantly reduced performance is undesirable. Even though a warning is provided to the driver, he can elect to ignore it. With U.S. designs, the vehicle can be operated a short distance (to allow the driver to proceed to a safe place to stop) before the parking brakes apply.

Emergency system tests were run on the two combinations discussed earlier. Figures 5 and 6 show the results. Failures were introduced into the primary systems on the tractors (Figure 5) and then the secondary systems (Figure 6). The tractors were towing fully loaded trailers for these tests, and all stops were "full treadle" applications from 20 mph (32 km/h).

FIGURE 5. Comparison of loaded combination vehicle performance with tractor primaries failed.
FIGURE 6. Comparison of loaded combination vehicle performance with tractor secondaries failed.

It can be seen in both Figures 5 and 6 that performance for the first stop after the failures on both the U.S. and European vehicles was similar. For both types of failures the U.S. vehicle showed a steady increase in stopping distance as more stops were made until the spring actuated parking brakes began to drag and the test was terminated. Performance of the European vehicle, on the other hand, remained relatively constant and could have been continued indefinitely.

3.2 Trailers

Emergency brake systems on U.S. trailers are essentially the same as the parking brake systems. FMVSS No.121 requires that the emergency brakes apply when the supply line to the trailer is vented to atmosphere, such as when the trailer breaks away from the tractor. The majority of U.S. trailers employ spring brake chambers (in series with the air chambers) at each foundation brake to provide the emergency and parking function, although this is not the only type of system possible under the U.S. standard. Air-applied mechanically held systems are also allowed if they meet certain criteria.

European trailers do not employ spring brakes for either emergency or parking. For emergency braking they use a valve known as a relay-emergency valve. This valve senses supply-line pressure and if it falls below a preset level the valve operates to "dump" whatever air is currently available in the trailer reservoir into the service brake chambers. This is the same basic valve that was used in the U.S. on trailers and converter dollies prior to the
effective date of FMVSS No 121 and is still used on converter dollies today.

4.0 PARKING BRAKE SYSTEMS

Almost all U.S. and European powered vehicles utilize spring brakes for parking although both the U.S. and European standards do permit other approaches (such as air-applied parking brakes) as long as a mechanical holding feature is provided. U.S. vehicles usually have spring chambers on one or more of the drive axles. In European vehicles, spring chambers are sometimes provided on steering axles.

Trailer parking brake systems on U.S. and European vehicles are very different. Most U.S. trailers employ spring brakes on all axles, although FMVSS No. 121 does permit other types of systems as long as a mechanical backup is provided. European trailers typically feature a hand crank mechanism that operates through a system of cables and levers to apply the foundation brakes. To "park" European trailer, the driver must first apply the tractor parking brakes, then exit the vehicle and walk back to the rear of the trailer and "crank" on the parking brakes. European tractors usually have a valve that allows the trailer to be "parked" on air while this process is taking place.

Parking brake tests were run on the U.S and European combinations discussed earlier by attempting to park them on a 20 percent grade with the trailers fully loaded. The U.S. vehicle, which has spring brakes on three of its five axles (one drive, two trailer axles), held in both directions. The European vehicle with spring brakes on two of the tractor axles (front and one drive) would not hold in the uphill direction unless the trailer hand-operated parking brake was "set."

5.0 SUMMARY AND CONCLUSIONS

Braking systems on U.S. and European heavy vehicles are very different and these differences are apparent in the service, emergency and parking portions of the systems. These hardware differences are due to disparities in the regulations and in the design philosophies on both continents. The most significant point of divergence is the manner in which braking forces are distributed in the service brake system among the various axles because this can impact performance in the most common accident avoidance situations.

European heavy vehicles typically utilize more braking at the steering axle (although this only applies to heavy vehicles with air brakes and not those with hydraulic brakes), and they utilize load-sensing proportioning valves that are not found on any U.S. heavy vehicles. Calculations and simplified vehicle dynamics theory indicate that European vehicles should exhibit superior braking efficiency under all loading and road surface conditions.
primarily because their brake forces are more closely balanced to their dynamic axle loads. Recent experiments comparing a European combination and a U.S. combination indicate that this is not necessarily the case, however.

Braking tests conducted at various trailer loads (as well as with bobtail tractors) in various simulated accident avoidance maneuvers indicate that the U.S. vehicle could outperform the European vehicle in a number of cases. When the U.S. vehicle was not equipped with an automatic front-axle limiting valve (these devices are an optional equipment item and are installed on many U.S. vehicles), the U.S. vehicle outperformed or was within ten percent of the performance of the European vehicle in 13 of the 24 cases evaluated. With this limiting valve, however, this "close to or better than" performance condition was achieved by the U.S. vehicle in only 6 of the 24 cases evaluated.

The European tractor significantly outperformed the U.S. tractor in all bobtail tests unless the U.S. tractor was equipped with a bobtail proportioning system (another brake equipment option available on U.S. vehicles). With such a device the U.S. tractor was able to equal or exceed the performance of the European tractor in all cases except the high coefficient of friction (dry road) case. Here the European tractor stopped 25 percent shorter primarily due to its larger front brakes (the U.S. tractor could not lock its wheels on the dry surface).

It is possible that some differences between "theory" and experiment may be explained by two factors. First, the load-sensing valves did not perform in accordance with the simplified way in which they were "modeled" in the calculations and, second, the definition of limit performance used in the calculations did not agree with the "real" limit in the tests. The calculations assumed that the limit would be reached (i.e., loss of control would occur) when only one axle of the tandem axles locked. In the tests it was found that both axles needed to be locked before control loss occurred.

The primary difference in the performance of the emergency brake systems on U.S. and European powered vehicles with air brakes is the fact that U.S. vehicles cannot continue to operate indefinitely with a failure in the pneumatic system. After some number of stops the parking brakes will apply. With a European vehicle, intact reservoirs can be replenished and partial system performance can be maintained indefinitely. European trailers employ relay-emergency valves (such as used on U.S. converter dollies) for emergency braking capability, whereas U.S. trailers utilize their parking brakes (usually spring actuated) to serve this function.

Although parking brake systems on powered vehicles are essentially the same between the U.S. and Europe, trailer parking brake systems are significantly different. European trailers employ a hand crank mechanism that must be activated by the driver after exiting the vehicle and standing beside the trailer to operate it. U.S.
trailers use spring actuated brakes (or other approved devices) that are activated via a control knob in the tractor.

6.0 REFERENCES


Braking Safety of Heavy Vehicle Combinations in the Nordic Countries

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Braking Safety of Heavy Vehicle Combinations in the Nordic Countries

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ABSTRACT

In many countries, official statistics indicate that Heavy Goods Vehicles (HGVs) are overrepresented in fatal accidents. The absolute numbers of annual HGV fatalities are also important incentives for preventive measures.

The mass in itself make HGVs very aggressive when impacting to other road users. For instance, a head-on collision between a fully loaded HGV and an ordinary car, both at 50 km/h, will expose the car occupants to the same velocity change as a barrier collision at almost 100 km/h. So, as long as special deformation zones are missing in HGVs, their active safety is of utmost importance.

Experimental studies and theoretical analyses have revealed numerous accident avoidance problems with HGVs, due to their great dimensions and variations in weights. The articulation needed for manoeuvrability at low speeds creates stability problems at highway speeds, particularly during braking. This was supported by evidence from a recent case-control study in the U.S.

A similar research program was opened during 1986/87 with measurements of decisive quantities in the air brake systems and of the braking characteristics of HGVs in the Nordic countries Denmark, Finland, Norway, and Sweden. In each country 100 HGV-combinations were randomly selected from the normal traffic flow on suitable roads to achieve results representative for the four vehicle populations.

Both the overall deceleration performance and the brake force distribution were measured directly by driving and dynamometer tests. Also recorded were weight distributions, brake and wheel size, push rod stroke, load sensing valve amplitude, etc.

Wheel lockup observations are related to simultaneous deceleration and control pressure measurements. The deviations between ideal and recorded influence from load sensing devices are evaluated. No Antilock Brake Systems, ABS, were found in these vehicle samples.

Data indicate that only a minority of the HGV-combinations in use will reach the minimum deceleration performance (5 m/s²), required in legislation. Substantial braking property differences have been found between the countries. Explanations are suggested on the basis of distinct internordic deviations in legislation and vehicle design.
Safety Aspects of Heavy Goods Vehicle Design

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Safety Aspects of Heavy Goods Vehicle Design

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This paper reviews developments in design to improve the safety of heavy goods vehicles (HGV) in the UK. TRRL undertook a systematic programme of research, beginning in 1980 with data on and analysis of fatal HGV accidents. It was clear that the major risk was to other road users rather than the occupants of the HGV itself, though ejection was an important cause of death and injury to the HGV occupants, and restraint systems and stronger cab construction would be beneficial. Rear guards to protect car occupants in rear-end collisions, and side guards to prevent cyclists and pedestrians falling between the wheels, are now in general use. Energy-absorbing front underrun guards are now almost fully developed, and are capable of protecting the occupants of even a small car in a head-on collision up to closing speeds of 60 kph (40 mph). TRRL began experimenting with anti-lock brake systems on HGVs over twenty years ago, but these systems are only now coming into widespread use. Mandatory fitment after 1991 should improve the braking and stability of HGVs considerably. The paper concludes by discussing other aspects where the safety of HGVs might be improved.
SAFETY ASPECTS OF HEAVY GOODS VEHICLE DESIGN
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1. INTRODUCTION

In the UK, Heavy Goods Vehicles (HGVs — goods vehicles defined for various purposes as having either an unladen weight exceeding 1.5 tonnes or with a gross weight exceeding 3.5 tonnes) form only 2.7 per cent of the total road vehicle fleet, but account for 8.1 per cent of the total vehicle distance travelled. Their importance to the national economy is obvious, and relatively greater than in physically larger countries where line-haul distances are longer and more suited to rail haulage. There has been a long-established trend towards heavier vehicles. Between 1977 and 1987 the total HGV fleet actually declined by 8 per cent, but it carried 14 per cent more tonne-km (Transport Statistics Great Britain, 1980). Between 1983 and 1987 (a change in definition precludes a longer comparison period) the number of articulated HGV tractors plated at over 33 tonnes increased two and a half times, while the number below 33 tonnes declined by 28 per cent (Department of Transport, 1988). Because much of the British road system, and especially its bridges, was not designed for very heavy vehicles the current maximum weight limit (for articulated vehicles with 5 or more axles) is 38 tonnes, but this will rise to 40 tonnes in 1999.

Accidents involving HGVs account for 5.7 per cent of all injury road accidents in the UK, so their involvement is rather lower than their share of total vehicle distance travelled. With professional and highly-trained drivers, and with a large proportion of travel on inter-city roads, a lower-than-average accident rate might have been expected. Even so, it may well be that this potential advantage is offset to some degree by the intrinsically poorer handling and braking of heavy vehicles. Certainly, there is scope for improvement in the primary safety of HGVs.

More significantly, however, fatalities form a higher proportion of all casualties, at 3.7 per 100 million vehicle-km, in HGV-involved accidents than in all road accidents (2.5 per 100 million vehicle-km). This is not surprising: in collisions between two vehicles the lighter vehicle generally comes off worst, because heavy lorries have particularly "aggressive" structures. They have a much larger mass than most other road vehicles, so that they suffer a smaller velocity change when in collision, and their structure tends to lie higher than the energy-absorbing structure of cars, and they are generally considerably stiffer. If they are to cause...
less damage to smaller vehicles, their structure needs to be made more compatible with that of other road vehicles. This requires that, in collision, their structure should link strongly with the energy-absorbing sections of a car's shell, and that, preferably, they should themselves absorb an appreciable part of the collision energy.

2. ACCIDENT DATA

Although the routine accident reporting system in the UK provides some useful information about the involvement of HGVs and the severity of the injuries produced, detailed information of the sort which can identify accident causes and injury mechanisms requires a specific in-depth study of a sample of accidents. This type of study is very expensive, and it is only possible to fund such studies at fairly infrequent intervals. The last study of this type in the UK used data collected in 1976 (Riley and Bates, 1980, and Riley, Chinn and Bates, 1981), but there is no reason to believe that a more up-to-date study would come to very different conclusions.

In Riley et al.'s study of 740 fatal accidents involving 812 HGVs and causing 844 fatalities, only 67 HGV occupants were killed, i.e. 8 per cent of the total fatalities. Not surprisingly, given the size and solidity of HGVs, it is other road users who are most at risk in HGV accidents: 46 per cent of the fatalities were car occupants, 19 per cent pedestrians, 13 per cent motorcyclists, and 6 per cent pedal cyclists. A generally similar breakdown has been observed in other countries (European Experimental Vehicles Committee, 1987). Consequently, although it is important to consider how better protection might be afforded to HGV occupants themselves, the priorities would seem to be to attempt to reduce the accident rate by improving primary safety, and to design the vehicle to be less aggressive to other road users, especially to cars. In countries such as Sweden or the USA, where line-haul distances tend to be longer and roads less congested than in the UK, the proportion of HGV accidents which involve no other vehicle is considerably higher than the 7 per cent found in the UK, and so the issue of HGV occupant protection is correspondingly more important, but protection of other road users is likely to be the dominant aspect everywhere.

It is generally difficult to establish the extent to which better design of vehicles might have avoided an accident altogether, or have reduced its severity by reducing the speed at impact, since the causes of an accident are often manifold, hard to identify unambiguously after the event, and obscured by attempts
at post-hoc justification as the drivers involved are reluctant to admit to error. In the study of HGV-involved fatalities, however, the driver lost control prior to impact in only 93 out of the total of 812 HGVs (Riley et al, 1981). In only 34 of these cases was it considered likely that improvements in vehicle design would have prevented loss of control: 22 of these vehicles were articulated, and 13 of those jack-knifed. Improvements in braking and handling seem unlikely to make a major impact on HGV accident rates, therefore, though if better braking can reduce stopping distances it could avert some of the accidents where there is no loss of control but the vehicle fails to stop in time.

Forty-four of the HGVs rolled over, 22 of them in single-vehicle accidents. In 13 cases the vehicle rolled under cornering, without having struck any obstruction. In roll stability, and handling generally, the high centre of gravity of HGVs gives cause for concern, but there seems little practical prospect of improving this aspect. Fifty-eight lorries shed their loads, some 10 per cent of the three-quarters of lorries which were loaded, though in another 30 cases the load moved. It is only when two HGVs collide, or when an HGV impacts a large immovable object such as a bridge parapet, that load movement is a problem, although it is these high-mass impacts which account for 60 per cent of the HGV occupant fatalities.

3. PRIMARY SAFETY

3.1 Braking

The Transport and Road Research Laboratory has a long experience of research into anti-lock brake systems (ABS), beginning with systems for passenger cars in the early 1960s, assessment of the Dunlop Maxarret system as applied to HGVs in the late 1960s, and extending the work to motorcycle anti-lock systems in the 1970s.

Full development of commercially available systems has been a long time coming, but they are now commonplace, with some 50 to 60 thousand HGVs in the UK fitted with some form of ABS. The US Regulation FMVSS 121 was perhaps premature in requiring ABS on heavy vehicles in the mid-1970s, and the sudden large demand encouraged the setting up of manufacturers with little experience of ABS. Many of their products proved to be unreliable, and the experience brought ABS into disrepute. Failure of ABS on an HGV, where it serves the purpose of load sensing and anti-jacknifing devices, can be much more dangerous than on a car, and for this reason load-sensing devices may be retained: they also have the advantage of reducing brake lining wear, even when ABS is fitted. When ABS fails, and it is the wheel speed
sensors which fail most frequently, it is important that a clear warning is provided to the driver.

In 1991, EC Directive 71/320/EEC requires that all articulated tractor units plated at over 16 tonnes gross, together with all long-distance buses and coaches over 12 tonnes, will be fitted with Category I ABS (individual control on each wheel), while trailers will have Category III systems (which generally provide select low on one axle only of a bogie). This should greatly reduce the category of accidents where driver control is lost before impact, and shorter braking distances will help avoid or reduce the severity of other accidents too.

It will however be important to ensure that ABS systems continue to work reliably in the harsh environment of an HGV, and appropriate diagnostics may be required to indicate failure or incipient failure at periodic mandatory testing. This could be difficult to achieve without specialised and expensive equipment at testing stations. The wheels may have to be turning at anything up to 11 km/h before the speed sensors can be properly checked, for example. Protection of such electronic devices against electromagnetic interference is also important (especially in view of the relatively high-power radio transmitters carried by some HGVs), though TRRL's examination of this aspect so far suggests that adequate protection should not be difficult to achieve.

Very large vehicles are inherently more difficult to drive than light vehicles, and the very high standards of handling prevalent on small vehicles cannot be expected to apply to HGVs. As noted above, the high centre of mass makes them much more prone to rollover on cornering, sometimes at very low speeds with articulated vehicles. Since the whole point of HGVs is that they provide the capacity to carry bulky and heavy loads, little improvement can be made here, though baffling of liquids in tankers is helpful.

Power-assistance and a range of electronically-controlled mechanisms are making the vehicles very much easier to drive. This has potential dangers, too, however, since it becomes possible to handle the vehicle in ways which cause instability whereas previously the physical effort required discouraged such behaviour. It is important, therefore, that the new electronic systems provide the driver with adequate feedback to know when the vehicle is approaching instability. Indeed, 'intelligent' electronic systems have a growing potential to monitor conditions and either warn the driver when he is likely to get into trouble, or modify the vehicle's response to prevent the dangerous situation developing. The latter approach requires a high degree of confidence that the automatically-
modified response will be safer than allowing the driver to use his judgement on receipt of a warning.

3.2 Body design

Given their size, conspicuity of HGVs might not be expected to be a problem. Nevertheless, in the HGV fatality study sixteen per cent of the cars involved ran into the side of the lorry, and almost a quarter of the motorcycle fatalities hit the rear of a lorry. In two-thirds of the latter cases the HGV was stationary, but it was dark in only a quarter, so better rear lighting does not seem to be a major issue. Poor vision, possibly caused by heavy rain on motorcyclists' visors, seems to be a more serious problem, though it could be argued that more conspicuous colouring of the lorry rear would help. In this respect, HGVs are better than cars, since they are required to carry high-contrast and reflective chevron markings.

Accidents caused by other vehicles running into the sides of HGVs are perhaps more indicative of conspicuity problems, though it may also be a case of drivers not anticipating quite how long HGVs can be. More chevron markings along the side, and at night side lights at more frequent intervals, could be helpful.

One aspect of HGVs considered by motorists to be especially irksome is the spray they cause when running on wet roads (Baughan et al., 1983). This makes driving very unpleasant for anyone travelling behind, and overtaking is difficult and dangerous. Since 1984 most types of the larger HGVs have had to be fitted with spray suppression equipment around the wheel arches and this has gone some way to reducing the problem, but for large vehicles the amount of spray generated depends crucially on the aerodynamics of the vehicle, and spray entrapment around the wheels can only be of limited utility. TRRL is currently developing a methodology to relate physical measures of spray to the nuisance caused to drivers, as a prerequisite to developing more effective spray-reducing methods, but aerodynamic work (Allan and Lilley, 1983) has already demonstrated the extent to which a clean airflow around the vehicle is likely to reduce the generation of spray. Good aerodynamics can be achieved by streamlining panels between the front and rear wheels, cab-top deflectors and, for articulated vehicles, baffling the space between cab and trailer. Additional benefits would be better fuel economy and, important to safety, less turbulent airflow to buffet overtaking vehicles, and better stability of the vehicle itself. Streamlining at the levels of the wheels might also be used to improve conspicuity and to cover underrun guards: the latter aspect will be discussed in Section 4.
3.3 **HGV occupant protection**

Although in the UK HGV occupants suffer only a small proportion of the injuries caused by accidents involving HGVs (8.5 per cent of the fatalities, 18 per cent of serious injuries), this still amounts to some 75 deaths and 700 serious injuries per year. The study of fatal HGV accidents found that one-third of the fatally injured occupants were ejected from the cab, and half were trapped and crushed by intrusion into the cab around the occupant's seat. The remainder were thrown from the seat and impacted the cab interior, or were thrown to some other part of the cab and crushed there. Thus protection could be improved by preventing ejection, and by reducing intrusion into the cab.

Ejection might be reduced by fitting the windscreen more securely, so that it would not become detached when distortion of the surround was only minor. Roughly one-third of those ejected might have been retained in this way. But the obvious way to prevent ejection is to use seat belts. Riley et al (1981) estimated that lap and diagonal belts would have saved the lives of 35 per cent of the HGV occupants in their study, and lap belts alone would have saved 29 per cent. HGV drivers argue that seat belts would prevent them escaping from a shifting load or an intruding cab. In a few cases this may be true, but intrusion and shifting of the load happen very quickly in a collision and the number of occasions where an occupant could move to avoid them is considered to be negligibly small. This type of argument has been used against car seat belts where it is clear that any disbenefit in certain circumstances has to be set against an overwhelming advantage. Even so, seat belts present more practical difficulties in an HGV than in a light vehicle. The higher levels of vibration and bounce, especially with suspended seats, cause problems with locking of inertia reels, and HGV cabs generally require a greater reach than does a passenger vehicle. Nevertheless, design of satisfactory belts should be perfectly feasible. Air bags would offer some protection, though they are more limited than belts: they are only effective in frontal collisions, but frontal impact accounts for almost half of occupant fatalities.

Overturning accounts for most of the remainder, and strengthening the cab structure so that the roof can withstand the weight of the overturned vehicle would be beneficial in many of these cases. It has to be accepted, however, that it is not practical to strengthen the cab to the point where intrusion could be prevented in HGV to HGV collisions, or in collisions with solid objects such as bridge abutments.
4. PROTECTION OF OTHER ROAD USERS

Table 1 shows the breakdown of fatalities to car occupants, two-wheel riders and pedestrians (Riley and Bates, 1980). Protection in frontal impacts is clearly a priority requirement for car occupants, and front impact is also the major category for motorcyclists and pedestrians, but side impact is dominant for pedal cyclists, and also features more frequently for motorcyclists and pedestrians than it does for car occupants.

| Direction of impact of other road users with HGVs (in brackets) (Riley and Bates, 1980) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Direction into HGV              | Car             | Motor cycle     | Pedal cycle     | Pedestrian      |
| Front                           | 222 (66)        | 42 (41)         | 17 (37)         | 89 (59)         |
| Side                            | 56 (16)         | 32 (31)         | 26 (57)         | 49 (33)         |
| Rear                            | 46 (14)         | 26 (26)         | 1 (2)           | 5 (3)           |
| Other                           | 14 (4)          | 2 (2)           | 2 (4)           | 8 (5)           |
| TOTAL                           | 338 (100)       | 102 (100)       | 46 (100)        | 151 (100)       |

Motorcyclists feature disproportionately in rear impacts, but this may be a problem of visibility as discussed earlier. The widespread requirement to fit rear underrun guards, to EEC Directive 79/490 in Europe, should have reduced injuries to car occupants, and might have been of some limited benefit to two-wheelers also, but collection and analysis of more recent accident data is necessary to demonstrate this. TRRL hopes to update its own studies in the next few years. The almost universal wearing of seatbelts in the UK, as in most other European countries, has increased the advantages of rear underrun guards: without seatbelts the occupants were thrown forward and came into contact with the rear of the lorry, with or without a guard.

Sideguards are now mandatory in the UK, but it is not practicable to build them to a strength which can protect against lateral impact from a car: the guards are long, and would weigh too much. Even so, the much slimmer guards required to deflect two-wheel riders and pedestrians from falling under the wheels are generally built to a higher standard than the prevailing requirements to withstand 2 kN with a deflection less than 150 mm, and they can be of benefit to car occupants in angled collisions to the side. It is estimated that
sideguards should save 50 to 60 fatalities per year, to pedestrians, cyclists and motorcyclists (Riley et al, 1985). However, present sideguards are probably less effective than this, because they offer too much ground clearance, and too much clearance around the wheels, to prevent a body rolling in. TRRL tests suggested that clearances should preferably be no greater than 400 mm, whereas operators preferred a much greater clearance, and the current specification is 550 mm. There is a particular problem with articulated trailers since the height of the fifth-wheel linkage varies, so that both trailer and sideguard often rise towards the front, giving a much larger ground clearance there than specified (Figure 1). If the emphasis on aerodynamics were to increase, bringing all the benefits discussed in Section 3.2, and possibly encouraged by a move to better fuel efficiency as concern mounts over the Greenhouse Effect, it is interesting to note that one result might be more effective side protection. Aerodynamic side skirts may well provide smaller ground and wheel clearances, the panelling would avoid any problem with pedestrians or two-wheel riders being struck by the upright supports of sideguards, and the plane surface would offer the potential for improved conspicuity.

Protecting pedestrians or two-wheel riders in frontal impacts is a fairly intractable problem. It is possible that some of the lessons learned in TRRL’s work on car fronts (Harris, 1989; Lawrence, 1989) might be transferable to treatment of HGV fronts, but their vertical planes provide unpromising material.

There is, however, much that can be done to improve the protection offered to cars in frontal impact. In the past two decades there has been considerable development in the energy-absorbing properties and collapse rates of car fronts, as required by EEC Directive 74/297 and US Regulations FMVSS 203 and 204. This has been of little benefit in car to HGV impacts, because the energy-absorbing structure lies below the height of the major structure in the HGV. The lorry front merely ploughs across the top of the car bonnet and on into the passenger compartment. It is not uncommon for car occupants to be struck directly by parts of the HGV. An underrun guard can connect the HGV structure into the energy-absorbing structure of the car. Front underrun accidents tend to occur at higher closing speeds than rear underrun, however, and as well as having a strong structure at car base level it is desirable that the front underrun guard itself provides some energy absorption.

TRRL testing has concentrated largely on guards supported by ‘invertubes’ (Figure 2) which absorb energy at compressive forces greater than 50 kN by turning a welded steel tube ‘inside out’, rather like reversing a
Figure 1. Standard sideguard fitted to articulated semi-trailer, showing increase in ground clearance towards front.

Figure 2. HGV front underrun guard, showing energy-absorbing "invertubes".
Tests have also been done successfully using hydraulic and butyl-rubber energy absorbers. In full-scale impact tests between a small 750 kg car and a 5.3 tonne lorry, at a closing speed of 64 kph, the reduction in intrusion into the car passenger compartment with the underrun guard in place was dramatic (Figure 3). Tests have been done using both stationary and moving lorries, and with larger cars.

A method of estimating the energy absorbed by the guard has also been developed. This consists of propelling a mobile barrier of mass 250 kg at 50 kph into the stationary underrun guard, impacting in the centre and at the drop arms, and possibly near the end of the guard. From the deceleration of the trolley and the displacement at the point of impact the energy absorbed may be estimated. The systems tested by TRRL have proved capable of absorbing 20kJ.

As a result of the full-scale and trolley work, TRRL has developed a specification for an underrun guard. The original intention (Riley et al, 1987) was for a guard to meet the requirements of a static and a dynamic test. The static test was to have been similar to the existing Directive requirement for rear guards insofar as it would have had specified dimensions and ultimate strength. The proposed dynamic test was the trolley test described earlier, intended to ensure that the guard absorbed a specified minimum amount of energy.

It is now considered, however, that a simpler but satisfactory requirement would be to replace the two separate tests with one static test. This would involve loading the guard at various positions across its width and measuring its deflection as the load was increased. The guard would have to absorb defined amounts of energy without exceeding a maximum deflection. While absorbing energy the load should not exceed defined values but afterwards an ultimate strength should be satisfied. The guard should also satisfy dimensional requirements.

Manufacturers of energy-absorbing systems for which the above procedure would be unsuitable, for example speed-dependent mechanisms such as hydraulic rams, would have to satisfy the Department of Transport in other ways that the proposed system was suitable.

Work in Germany at HUK Verband has tackled the problem of front underrun energy absorption using stiff honeycomb foil (Danner et al, 1989; Gruettert et al, 1989), but the principle is the same.

In the UK, it is estimated that front underrun guards on all HGVs would save 60 to 70 lives per year, and cost-benefit calculations indicate that there would be a net benefit if the protection could be provided within a
Figure 3. Results of impact tests with small car, without (a) and with (b) an energy-absorbing front underrun guard. Both HGV and car moving at 32 kph, closing speed 64 kph.
cost limit of £150. If the underrun guard has to be retrofitted it may not be possible to come within this budget, but it would certainly be possible to build these principles into new HGVs at less cost than this.

Again, a move to greater streamlining may dictate lower front structures and less ground clearance. Certainly, 'concept' HGVs for exhibition often have very little ground clearance. But operators are not keen on the 300 mm clearance proposed, even though front guards are normally fairly close to the front wheels, where ground clearance is less of a consideration than with sideguards or rearguards. Manoeuvring of lorries in loading bays and on ferries etc tends to dictate a clearance which is greater than that at which underrun guards are fully effective. In the end, it might be cheaper to modify HGV facilities to cater for a lower ground clearance than to accept higher clearances on the vehicles themselves.

5. CONCLUSIONS

1. It seems likely that better braking systems fitted to HGVs would help reduce the number of accidents and the severity of the impacts in which they are involved. Worthwhile safety improvements might also be achieved by changes to basic HGV design to reduce the tendency to overturn, to provide more effective spray suppression, and to improve conspicuity for the rear and side. However, the available data is generally inadequate as a basis for estimating the saving in accidents and injuries which might be achieved by any proposed measure, and more in-depth accident data is needed for a proper assessment of the extent to which HGV primary safety might be improved.

2. With the increase in the complexity of electronic 'safety' systems being fitted to HGVs, there is a growing need to develop equipment to check their integrity at regular intervals.

3. Because of the mass and stiffness of HGVs, HGV collisions are more likely to cause fatalities and serious injuries to occupants of other vehicles involved than to the HGV occupants themselves. There is therefore a need for guards to be fitted to the front and rear of HGVs to protect occupants of smaller vehicles. The guards should preferably be energy-absorbing, to ensure higher survivable impact speeds. Many countries already require rearguards.

4. There is a need for lightweight sideguards to be fitted to HGVs to protect pedestrians and riders of two-wheeler. These are already specified in some countries, though they are not always as effective as
they could be.

5. Seat belts fitted to HGVs would prevent many occupant fatalities by preventing ejection from the cab, but some development of belt design is required to make belts more convenient for use in HGVs.

6. Stronger HGV cab structure would prevent some HGV fatalities: the number of lives which could be saved in the UK is not great, but it is a more important aspect of HGV safety in some other countries with longer journey distances and more lightly-trafficked roads.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


Advantages of a Comprehensive Risk Analysis in Road Engineering

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Risk Analyses in Highway Engineering

- Abstract -

New and difficult tasks in highway design such as realignment or upgrading of existing or evaluation of different alternatives for the construction of new roads have created a need for disaggregated information about the safety level of the projects in question. This information cannot be gained in the conventional way mainly based on the technique of accident analysis because of its fundamental methodological deficits. Risk analyses - already well-known from other technical fields - appear to be a possible resolution to this information deficit.

This paper summarizes the results of a research study carried out from 1986 through 1987 at the Technical University of Darmstadt. The aim of the study was to find out whether risk analyses can be successfully applied in traffic safety research. The method is already well-known from its wide use in the field of design of nuclear power plants and chemical factories. Because of the different type of application, it was necessary nevertheless to adapt the method for the use in a completely new field.

Although there are quite a number of elements and procedural details that require to be changed or added, the study has proved feasibility and usefulness of the application of risk analyses in traffic safety research.

The main advantages which can be expected from the use of risk analyses are the following: it requires teamwork of different research groups from various branches of science and thus promotes interdisciplinarian cooperation. The knowledge acquired may be refined and extended gradually and in sections according to the necessity of additional information and the research team's capabilities. The method supports immediate derivation of cause-effect relationships, in order to explain the reasons of single accidents. Above all it renders possible quantitative evaluation of different design alternatives for a given problem.

The address proposed will present the basic ideas and the main principles of the new method and demonstrate its application by a practical example.
ADVANTAGES OF A COMPREHENSIVE RISK ANALYSIS IN ROAD ENGINEERING
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Difficult tasks in upgrading and re-alignment of existing roads as well as the demand for disaggregated information for evaluating design alternatives in new projects have lead to an information deficit in traffic safety work in the past years. The information required cannot be gained by the existing tools due to fundamental methodological problems. Risk analyses appear to be a possible resolution to this information deficit. They are structured modularly and hierarchically, permit quantitative statements on safety and the cause-effect relationships of accident generation, encourage interdisciplinar collaboration and may be modified partially.

Maintaining and improving safety is one of the most important if not the most important goal in the field of transportation and therefore also in road design. Nevertheless, its realisation is getting more and more difficult.

The simple tasks of re-alignment and improving capacities have mainly been resolved. Now black spots of roads and road sections that show significant accumulations of accidents need to be treated. Rendering safe these dangerous parts of the road system has been postponed time and time again because of lack of evident possibilities for resolving the problems.

The design of new roads requires weighing increasingly restrictive environmental requests against traffic safety. Mainly when comparing alignment alternatives, disaggregated statements regarding traffic safety are necessary.

Moreover, decisions made in road design are frequently reviewed in court, so that they have to be understandable for non-professionals, too.

Therefore engineers working in road design need:
- guidelines for specific design tasks to be used in case of departure from standards, and
- methods to gain quantitative measures for traffic safety when comparing different alignment alternatives.

Safety research has to work out these methods and guidelines.

It is evident though that there cannot be absolute safety. In a world populated by living beings risks always exist, e.g. damages and injuries will occur with a certain probability. The goal of safety research is to perceive and describe these risks and reduce them where ever possible.

This is especially difficult in road engineering, because the individual behaviour of a large quantity of human beings has a strong influence on the system's overall behaviour. Human beings unconsciously evaluate the advantages and disadvantages of their actions (pictures 1 + 2). In doing so, they seem to accept a certain risk.
Some theories assume that any traffic safety measure will be completely compensated by the drivers' behaviour. This assumption is probably not true, because it has been proven that safety belts as well as "relation alignment" (e.g. limiting the variation of subsequent radii in horizontal curves) have lead to a significant diminuation of risk.

Safety research can thus not deny unconscious human evaluation (the "accepted" risk). Anyway, risks that exceed the "accepted" level should be avoided if ever possible. Moreover, it should be tried to keep the risk accepted by drivers as small as possible by influencing their evaluation process. The question though remains, how safety research can get the necessary information about the origins of risk.

According to the experiences made in the past, this information cannot be obtained by applying conventional methods such as accident analysis, because their information density is usually too small. In this context, it is especially important to mention that accidents are - statistically seen - very seldom events. Therefore, the variation is often bigger than the value of the statements derived themselves.

Thus, progress in safety research strongly depends on the exploration of more and new sources of information. Only when science knows, where and why certain risks originate, it can develop effective strategies to avoid them.

The structure of a model permits not only to reconstruct dependences already known, but also to regard relationships that are only supposed and still need to be verified. It is
also possible to consider analogies to other fields of science. Moreover, the
application of a model rather than the mere analysis of field observations facilitates
working out cause-effect relationships.

Observations are only used to calibrate the model and to confirm or abandon
supposed dependences. When the statements accessible to verification are
sufficiently in accordance with reality, the other statements generated by the model
are supposed to be close to reality, too. Thereby, it will be possible to make
statements on parts of the model not yet analysed or not accessible to observation.

In order to be able to work with a model over a longer period of time, its structure
should be hierarchical and modular as well:

- modularity and hierarchical structure allow replacing single parts without the
  necessity to newly develop the whole model (picture 3). Work starts with the
definition of a rough structure of the model and the integration of the information
already existing. Thereafter the circle "work with the model - identification of
weak-points - work with the model" is repeated. Working with the model shows
not only its always existing weak-points, but mainly provides the data later to be
used in practical design. It is necessary to mention though, that the identification
of weak-points will only take place in parts of the model and the usually far larger
rest of it will remain unchanged and can be used further. Moreover, modularity
encourages the collaboration of various research groups from different branches
of science at the same model.

- an identical structure permits proceeding the analysis of observation data by
  computers. Through this, larger amounts of information can be proceeded with
  the same human resources.

![Picture 3: Most important work phases](VTI RAPPORT 351A)
In addition to these requirements, a model used in road engineering has to take into account that:

- the branches of science collaborating are very different one from each other (engineering, medicine, psychology, pedagogy; picture 4). This is reflected in the way of thinking and communicating. Nevertheless, all these branches should be working at the same model.

- it is very difficult to describe systematically human behaviour. It is thus extremely important to distinguish between risk as an impartial factor and risk as it is individually perceived by human beings.

- accidents happen only if a number of unfortunate events coincide. This linkage of negative casualities has to be taken into account by the model.

**Picture 4:** Analysis of road traffic requires participation of many different branches of science
Picture 5: Damages occur only if a number of unfortunate events coincide

A model of this kind has been developed in its basic outlines at the Department of road design and road operation of the University of Darmstadt. For the development of the model elements and experiences from:

- risk analyses in chemical and nuclear engineering,
- finite-element-methods of civil engineering,
- probability theory, and
- operations research and process description in chemical engineering and economic sciences

have been used.

At the moment the first quantitative calculations are made.

The structure of the model is similar to the process plans already known, where states (equivalent to a defined point of time) and actions (equivalent to periods of time) are used to describe complex processes. To each state a number of parameters are assigned which describe the system at that point of time, and to each action rules according to which the parameters are changing with time.

In this scheme each action may be seen as a module and may be described more in detail by being split up in two or more sub-actions. The states are then serving as nodes.

Risk analysis does not aim at quantifying one single process, but the behaviour of the system "road traffic" as a whole. Therefore it does not make sense to fix the model to specified points of time. For this reason, situations are used instead of states and well-defined actions are replaced by more general processes (picture 8).
Picture 6: States correspond to points of time, actions to periods of time

Picture 7: Modularity by splitting up an action into a number of sub-actions

Picture 8: In order to describe system behaviour states become situations and actions become processes

To describe the situations statistical distributions (usually multi-dimensional) are used, which take into account the variety of possible behavioural patterns.

This method shall be demonstrated with an example, the "approach to an obstacle on the road". A first basic structure is derived from the linkage of unfortunate events (pictures 5 and 9).
The situations serve as nodes between the processes which can be revised and refined by different research groups (pictures 10 and 11). In this case, logically preceding process descriptions need to deliver only those variables and information which are needed in the subsequent processes. In the example the situation "vehicle approaches obstacle" could describe with which probability and which

- kind of weather,
- road conditions,
- type of road,
- speed, and
- driver disposition

vehicles are approaching obstacles of a defined type. The data need to be collected in the processes "obstacle generation" and "vehicle approach" and can be used in the processes "attempt to avoid danger" and "generation of damage".
damage generation

accident
- collision with obstacle
- leaving carriageway
- collision with other traffic

damage generation through collision with obstacle
- damage generation through leaving carriageway
- damage generation through collision with other traffic
- damage

Picture 10: Refining of damage generation

trial of danger prevention

vehicle approaches obstacle
- identify obstacle begin with reaction
- breaking

- avoiding obstacle

- skidding

- no accident
- collision with obstacle
- leaving carriageway accident
- collision with other traffic
- interaction with other traffic

Picture 11: Refining of damage avoiding
The processes are only describing what might happen as a consequence of the initial parameters. A variation of the probabilities of single events does not require a change of the process description. If, for example, mean speeds are increased, the probabilities of the situation "accident" can be derived with the same process description "attempt to avoid danger".

Analyses following this pattern might show that on roads with motor vehicle traffic only smaller vertical radii for connecting different grades can be accepted without compromising safety, because of the much lower probability of obstacles on the carriageway. Through this, alignment could be adapted more easily to the natural landscape.

Another application of the example would be the examination of a possible gain in terms of safety through the addition of paved shoulders on a planned new road section. A quantification of this gain could be the basis for a comparison with the additional consumption of land.

A comprehensive model can only be fully efficient if its main advantage, e.g. the collaboration of a large number of institutions, is really applied. In order to reach this goal the collaboration of many institutions, preferably from different branches of science, is strongly encouraged. An interdisciplinary committee should be established to coordinate the research activities.

With regard to the recent development of traffic accidents it is urgent to develop risk analyses for road engineering through case studies in the near future, because their application holds great advantages for transport policy, science and practical engineering.

Transport policy gains the opportunity to identify the weak-points of the road system through the cause-effect-relationships modelled. When searching for improvement possibilities, it may again refer to risk analyses in order to estimate the efficiency of measures proposed without long trials. The segmentation of the model into well-defined parts and the collaboration of different branches of science makes it possible to use limited funds more efficiently. The quantitative statements permit a better consideration of safety in the planning of new transport facilities. Above all, it is more easily possible to weigh safety against other requests to road design (mostly environmental aspects). Quantitative analyses in general make it possible to set realistic goals in transport policies and to control their realisation.

Science takes advantages from the cause-effect structure of the model which promotes explaining rather than merely describing procedures. The possibilities of interdisciplinary work and efficient use of funds have already been mentioned. Moreover, quantitative proceeding allows to identify trade-offs of different measures in the process of accident generation.

Practical traffic engineering is gaining new opportunities through additional information, decision criteria and evaluation tools to be applied, mainly to tackle dangerous road sections and in the case of departure from standards.
A New Method for Accident Analysis

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and

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New Methods for Evaluating Safety Measures
Using Accident Data

by Olga J. Pendleton
Texas Transportation Institute

The evaluation of the effectiveness of safety improvements using accident data has been a difficult task complicated by anomalies such as the regression-to-the-mean phenomenon, lack of control through traditional experimental design considerations, and insufficient sample sizes (e.g., accident frequencies and/or number of experimental units - sites). Statistical methods have been proposed to remove subjective biases which may confound conclusions in such cases. This study, funded by the Federal Highway Administration, examines various statistical procedures under a variety of applications to determine which procedures are most effective under what circumstances. Examples range from the simplest before/after design with no comparison group to multiple observations in time on a before/after with comparison group study. These procedures were applied to situations with few sites and high accident frequencies (such as changing posted speed on multilane high volume highway sections) as well as situations with many sites but low accident frequencies (such as signalization at intersections). Both actual and simulated data is used in these comparison. The sophistication of the statistical methods range from the most elementary procedures currently in use to more recently proposed sophisticated methods of Empirical Bayes estimation and time series analyses. Recommendations are made regarding which procedures are optimal for specific study designs. Also, design considerations are proposed which may alleviate problems and simplify the statistical analysis apriori to data collection.
A NEW METHOD
FOR ACCIDENT ANALYSIS

by

Olga J. Pendleton, Texas Transportation Institute
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Carl N. Morris, University of Texas

Sponsored by FHWA
NEW METHODS FOR ACCIDENT ANALYSIS

Abstract

Researchers in the field of accident analysis have long been aware of the problems associated with drawing statistical inference on safety using accident data. Aside from the problems of accessibility and quality, accident data present a real challenge when it comes to statistical analysis. This study addresses the problems of the statistical analysis of accident data and presents a new method (EBEST) for solving these problems. Three typical applications in accident analysis are considered - namely 1. the identification of high hazard locations, 2. the evaluation of safety treatments, and 3. the assimilation of information from multiple studies. A computer program (the BEAST) was developed to execute these analyses as a part of this study.
Accident data represent rare, low probability random events and, as such, typically follow a Poisson distribution. The classical statistical methods which are taught and for which computer software is readily available, are based on Gaussian principles - i.e. assuming normal distributions. This problem alone poses a serious impass to the appropriate analysis of accident data. However, even the more appropriate statistical methods which recognize the non-normality of accident data require certain assumptions which are frequently violated as applied to accident data. One such critical assumption is that of random and unbiased sampling.

Regression-to-the-Mean

Highway accidents are often used as a measure of effectiveness in evaluating improvements in a highway system. Classical statistical methods require that the highway locations to be evaluated for treatment effectiveness represent a random sample from a population of highway sections that might have received the treatment. In practice, of course, this seldom occurs. Highway sections are generally selected for treatment because the number of accidents at these sites is unusually high. Thus, these treatment sections represent a sample from the upper end of the distribution of the population from which it was drawn. Another sample drawn from this population at some future time (after treatment) would be expected to be closer to the center of the distribution. Thus, if a site has an unusually high number of accidents one year, the number of accidents at that same site the following year would, in all probability, be lower apart from any intervention at that site. This very real phenomenon is know as regression-to-the-mean (r-t-m). Figure 1 depicts the various degrees of the r-t-m phenomenon.

Note: this example is purely anecdotal and does not represent the real distribution of accident frequencies. The areas of the curve labeled A through D represent varying degrees of r-t-m potential from most severe to none. That is, if the treatment sites represent a sample from Area A, r-t-m potential is high. A subsequent observation on this same site is likely to be smaller as this value regresses to its true mean. If treatment sites represent samples from area D, they do, in fact, reflect a random sample and r-t-m is not likely to occur.

Regression-to-the-mean may be more of a potential problem for some safety measures than others. For example, it is probabal more serious in intersection signing and pavement markings than in construction zone projects or some treatment which is generally applied on the basis of non-accident based criteria. Regression-to-the-mean is also not likely to pose a serious problem in the identification of high hazard locations since the sample of locations which are being ranked, again, are usually selected on some non-safety related criteria such as highway type, etc.
Regression-to-the-mean has been recognized as a problem in data analysis in many fields other than transportation. It was recognized as a problem in transportation, specifically, accident analysis, for many years before any possible solution was offered. Hauer (1980) posed a method for adjusting for this bias using an Empirical Bayes (EB) procedure. Although the concept of this methodology has been widely embraced, actual use of this method in accident analysis has been limited. A few have recently braved this frontier (Higle and Witkowski, 1988), and Ben-Akiva and Cedar (1988)), but the method has not received widespread application. There are several possible explanations for this. EB methods are not traditionally taught and hence researchers in the transportation field are not familiar with it. The subject matter is difficult and has, for the most part, been explained in terms which require a certain degree of statistical training to understand. The computer software for executing the computations is not readily accessible. And finally, but most importantly, the data required for this procedure has not, routinely been used. Note that this does not mean that the data was not available. The necessary data is often available in some form but this data has been traditionally ignored in accident analysis. Specifics on this point will be addressed later.
Empirical Bayes Methods

For this application, our focus is on knowledge of the true accident rate for the entire population represented by the potential treatment sites. The Bayesian philosophy embraces the concept that each site has a true accident rate, $\lambda_i$, and that a group of $k$ such sites, $i=1,...,k$, would have means that would have the same distribution. Knowledge about this distribution allows the Bayesian to make probability statements about the true site means. The pure Bayesian assumes this prior information from some source other than the data. The Empirical Bayesian methodology used in this study assumes a prior distribution but estimates the parameters of this distribution using the data.

A necessary prerequisite to obtaining good estimates is having a data set which is representative of the entire population of interest. The non-Bayesian has this same prerequisite and attempts to meet this requirement by insisting on a random sample. The Empirical Bayesian attempts to meet this requirement by insisting on a suitable reference group. If, in fact, the sample is truly random and representative of the entire population, results from the non-Bayesian and Empirical Bayesian analysis may be somewhat similar. The more biased the sample, the more the benefit to be gained from the Empirical Bayes analysis. This, however, depends upon the data. Inadequate or inappropriate data can lead to false conclusions using EB methods just as faulty data can cause problems in any type of analysis. It is essential, then, that the data requirements be clearly understood by those attempting to use this method especially if the method is to be applied to data from a biased or non-random sample. (Such is generally the case in safety treatment evaluations.) One of the important data requirements is the availability of data on a reference group.

The Reference Group

The reference group and treatment group represent the entire population of potential treatment sites. If the treatment sites are selected in a biased way, the reference group will be the complement of the treatment group. Collectively, then, accident data on the treatment and reference group should represent the accident experience for all potential treatment sites. For example, if the treated sites were a group of urban intersections, a reference group could be all urban intersections with similar characteristics (roadway geometry, type of traffic, etc.) that potentially would have received the same treatment. Once the potential treatment group is defined, data is collected on a sample of sites representing this group to form the reference group. In practice, these sites will tend to have a lower accident rate than the treated ones or they would probably have been selected for treatment. The reason for this is in the treatment site selection process. The sites selected for treatment generally are selected because they have a high number of accidents.

In some respects, the reference group can be a comparison group. However, the current procedures for selecting a comparison group violate the prerequisites required of a reference group. There is a very important, though subtle, difference in the selection...
Comparison groups are selected for one primary purpose - to represent a time trend. There is no restriction that the comparison group must come from the same population as potential treatment sites. Indeed, sometimes the comparison group represents a completely different population - for example, when it represents a comparison condition like type of accident (dry versus wet) or time (day versus night). Clearly, daytime accidents do not have the same accident rate as nighttime accidents. Thus, daytime accidents do not constitute a suitable reference group for nighttime accidents but they may serve as a suitable comparison group by representing the trend in time from the before to after period.

However, a suitable reference group can be a suitable comparison group if these same sites are observed during the post treatment period. If the treated group is biasedly selected, then the reference group may also represent a biased sample, biased in the opposite direction. In this case, the reference group adjusted for this bias could be used as a comparison to also adjust for the time trend.

A word of caution is in order here. Using the reference group as a comparison group without adjusting for the sampling bias using the EBEST procedure could result in even more confounding of treatment effect. The unadjusted reference group would contain sampling bias and the observed post reference group would contain a time trend. These two factors would be confounded and could negate any treatment effects that might be present.

Of course, confounding can also occur if the comparison group is biasedly selected. If the comparison group does not represent a truly random sample and is somehow selected biasedly according to high or low accident experience, distortion will occur. Table 1 lists some examples of suitable and non-suitable reference groups for specific treatment groups.
Table 1.
Examples of Reference for Various Safety Treatments

<table>
<thead>
<tr>
<th>TREATMENT:</th>
<th>APPROPRIATE REF:</th>
<th>INAPPROPRIATE REF:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion to 4-way Stop from 2-way for urban intersections</td>
<td>All 2-way Stop urban intersections which could have been converted to 4-way</td>
<td>All urban intersections regardless of stop sign or signal type</td>
</tr>
<tr>
<td>Resurfacing of 2-lane roads that have not been resurfaced in two or more years</td>
<td>All 2-lane rural roads which could have been resurfaced and have not been resurfaced in the last two years</td>
<td>All 2-lane rural roads, even those that were just resurfaced</td>
</tr>
<tr>
<td>Raised pavement marker installation on two-lane unlit rural roads with curvature of more than some specified amount</td>
<td>Two-lane unlit rural roads with the same degree of curvature which might have been selected for treatment</td>
<td>All two-lane rural roads including lengthy sections with no curvature</td>
</tr>
</tbody>
</table>
The EBEST Procedure

The EBEST procedure assumes that accident counts are Poisson distributed about some mean and that this mean varies for each site $i$. These are assumed to come from a Gamma distribution whose two parameters represent the mean and variance of the population of potentially treated sites. The estimate of these parameters is based upon the accident counts and exposures at each site. Exposure may be traffic volume, section length, number of months, etc. The key to defining exposure for a given problem rests in the assumption of exchangeability which will be defined shortly. The conditional distribution of the accident counts given the Gamma distribution parameters (hyperparameters) is a negative binomial whose parameters can be estimated from the data using the method of maximum likelihood. This method of estimation requires an iterative numerical procedure for finding the estimates which will maximize the negative binomial likelihood function. These estimates are then used to compute the expected accident rate for each of the treated sites. This estimate is a value somewhere between the observed value for that site and the estimated true accident rate for the population of potential treatment sites. The amount that the observed value is adjusted by is called the shrinkage factor, $B_i$. If there is not much regression-to-the-mean, the value of the $B_i$ will be small and the estimated rate for site $i$ will be similar to the observed value. If the value of $B_i$ is close to zero, the estimated rate for site $i$ will be closer to the estimated rate for the entire population of potential treatment sites.

Empirical Bayes Assumptions

The assumptions on the probability distributions - namely, the Poisson for accident counts and the Gamma for the site mean rates, are reasonable and easily justified based on the nature of accident occurrence. However, there is one critical assumption in the EB methodology which requires careful scrutiny by the would-be user. This is the assumption of exchangeability. Basically, this means that we have no reason, in advance of data collection, to know which sites would have higher accident rates. This is best explained through an example.

Suppose that the only data available for a group of sites is their accident counts. Without any other measures of exposure, such as traffic volume, the accident count must serve as a surrogate for accident rate as it is the only available measure of safety. Suppose, now, that some very busy urban intersections are combined with low volume residential intersections in the treatment group. Before the data is even collected one could guess which intersection would have more accidents. In this example, the exchangeability assumption about the true site means is violated. To satisfy it, traffic volume data is necessary. In this way, the amount of information contributed by each site can be weighted by the traffic volume.

Although traffic volume is the most obvious variable which affects exchangeability, other variables can be a factor. For example, section length may vary among sites for some safety treatment studies. Another factor might be time periods. For construction zone treatments, duration of the construction period may vary. Collectively, these factors
can be termed exposure factors. If sites vary in their exposures, data representing these exposures is essential to the analysis.

In general, any information about a particular site which would allow you, a priori, to guess at the relative magnitudes of the site means must be included in the analysis. In a way, this is just common sense. If you were asked to compare sites using some measure of their accident experience, you would naturally take these factors into consideration. Therefore, a way to assure that you have sufficient data to satisfy exchangeability is to define the most appropriate measure of accident occurrence that would allow you to compare sites on a fair basis. That is, you would not compare accident counts for a site with 10 MVM to a site with 1000 MVM. But you would compare acc/MVM. You would not compare accidents per 10,000 ADT on a 5 mile section to a 10 mile section but you would compare acc/ADT/mile. You would not compare total fatalities for 3 years at one site to 2 years at another. But you would compare fatal accidents per year. In each of the above cases, not knowing a site’s MVM, section length, or time period violates the exchangeability assumption. These are all measures of the sites’ exposures.

The term exposure has been used but not defined explicitly. Exposure is a measure of a site’s relative accident risk. If sites have varying exposures, then some measure of their exposure is essential to satisfy the assumption of exchangeability. Exchangeability is a critical assumption in EB analysis and significant violation of this assumption will invalidate any results and conclusions drawn from the analysis, just as with any statistical procedure.

When is EBEST the BEST

A simulation study was conducted for varying degrees of regression-to-the-mean potential (values of $\alpha$), various treatment effects (values of $\theta$) and various sample sizes in both the treatment and reference groups. Samples were drawn as described in the section on a graphical representation of the big picture for the treatment group before treatment and the reference group. The treatment group accident count after treatment was randomly drawn from a Poisson distribution with mean $(1 - \theta) e$ to reflect the treatment effect. Five replications (repeated samples) were done for each combination of values of the simulation parameters ($\alpha$, n’s and $\theta$’s). A treatment effect was computed for both the EBEST and non-Bayesian method ($\hat{\theta}_{EB}$ and $\hat{\theta}_{r}$). These are specified in the notation section assuming the comparison group ratio is 1, i.e. no time trend. The average of the five replicate estimated treatment effects were then averaged. Other simulation criteria were also generated. Only general findings of the simulation study will be reported here.

- For small sample sizes (4 treatment sites and 10 reference sites) both methods were unsuccessful at detecting treatment effects up to a 50% reduction regardless of the amount of r-t-m potential.
For moderate sample sizes (20 treatment sites and 30 reference sites or 10 treatment sites and 40 reference sites), the EBEST method was substantially closer to the true treatment effect when the treatment effect was small (10% reduction) and the r-t-m potential was high. As the r-t-m potential decreased, the two methods did equally as well. Both methods were similar in detecting a greater treatment effect - 50% reductions.

For large sample sizes (40 treatment and 100 reference sites), both methods were similar at detecting a small treatment effect (10% reduction) at even the severest r-t-m potential ($\alpha = 0.5$).

The EBEST estimate was uniformly closest to the true treatment effect, i.e., even when the two methods were "similar", EBEST was closest. EBEST was also much closer on the average (small expected loss) in all cases.

In summation, the EBEST procedure is uniformly superior to the particular (naive) non-Bayesian method considered here, namely assuming that the best estimate of accident occurrence in the future is the number of accidents in the past. Thus, one would be safest to use the EBEST procedure regardless.

If the sample size (number of sites) is small, no method will be able to detect small treatment effects. The larger treatment effects may or may not be detectable but if they are, the EBEST procedure has the best chance of finding them.

If sample sizes are large, both methods will be able to detect even small treatment effects, but the EBEST method will be closest to the true effect.

If there is low or no regression-to-the-mean potential, i.e., a purely random sample, both procedures again are similar for moderate to large sample sizes, though the EBEST is closest to the true.

A Computer Program and Examples

A menu-driven computer program, the BEAST (Bayesian Estimation of Accident Safety in Transportation) is available for performing the EBEST analysis. This program is written in Turbo-Pascal and can be used on any IBM compatible PC with no supporting software. The program will perform either of two tasks, evaluation of a safety treatment or ranking according to accident occurrence. Short tutorials are available at the user's option for either task. Two examples with representative computer output follow.
SAMPLE OUTPUT FROM THE BEAST

Table 4 is a sample output listing from the BEAST for a safety treatment evaluation example. Descriptive statistics include the total accident frequencies (counts) for each group, treatment, reference and comparison, the maximum and minimum counts for each group, the maximum and minimum exposure value for each group, and the accident rate (count/exposure) for each group. The results from the EBEST analysis include estimates of the prior mean accident rate, MUHAT, and the mean exposure, RHAT, the average of the shrinkage coefficient for the treatment group, BAVG, the EBEST and naive frequentist estimate, THETAHEB and THETAF, of the treatment effect and another candidate frequentist estimate, THETAHFC, which will not be discussed at this time. The max and min accident counts for the treatment plus reference group are Max(z) and Min(z). Average exposure for the combined group (Avg(e)) and the ration of the largest to smallest exposure (ratio(e)) are also specified. Finally, a listing of the observed data for the treatment group after treatment is given for all sites or a selected subset of sites, depending on the user’s preference. The site id, observed counts(z), observed exposure(exp), and observed rate(y) for the treatment group after treatment are listed. These are followed by the expected EBEST rate for the site, the EBEST estimated accident rate for the site, the shrinkage coefficient, (Biz), the difference between the observed and expected counts(z-elambdahat), and the deviation of the observed from the expected accident rate (y-lambhat).

Table 4. Sample computer output for treatment evaluation

<table>
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<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>reference</td>
<td>before</td>
<td>11.00</td>
<td>3.00</td>
<td>2.00</td>
<td>390.30</td>
<td>198.00</td>
<td>39.20</td>
<td>0.03</td>
</tr>
<tr>
<td>treatment</td>
<td>before</td>
<td>30.00</td>
<td>7.00</td>
<td>4.00</td>
<td>226.63</td>
<td>75.95</td>
<td>22.40</td>
<td>0.13</td>
</tr>
<tr>
<td>treatment</td>
<td>after</td>
<td>22.00</td>
<td>6.00</td>
<td>3.00</td>
<td>226.63</td>
<td>75.95</td>
<td>75.95</td>
<td>0.10</td>
</tr>
<tr>
<td>comparison</td>
<td>before</td>
<td>24.00</td>
<td>7.00</td>
<td>2.00</td>
<td>349.70</td>
<td>160.00</td>
<td>31.50</td>
<td>0.07</td>
</tr>
<tr>
<td>comparison</td>
<td>after</td>
<td>24.00</td>
<td>8.00</td>
<td>2.00</td>
<td>349.70</td>
<td>160.00</td>
<td>31.50</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Empirical Bayes Analysis Results

<table>
<thead>
<tr>
<th>MUHAT</th>
<th>RHAT</th>
<th>BAVG</th>
<th>THETAHEB</th>
<th>THETAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10417</td>
<td>15.382</td>
<td>0.23904</td>
<td>0.5366</td>
<td>0.7333</td>
</tr>
</tbody>
</table>
For this example, a simulated data set was created wherein the true treatment effect was a 50% reduction in accidents. The treatment group before treatment was biasedly sampled from the upper 5% tail of its distribution (area A of figure 1) to reflect a high degree of regression-to-the-mean potential. The reference group before treatment was randomly sampled from the rest of the distribution. Twenty treatment and thirty reference groups were selected in this fashion.

After treatment the treated group was randomly selected from a population wherein the true mean accident was reduced by 50%. Exposures are generated from a negative exponential distribution ranging from 5 to 60. The true exposure for the simulation was 16. The true prior parameters then, were \( \mu = .2 \) and \( \lambda = 16 \). The estimates from the simulated sample were .104 and 15.38, respectively.

The average expected shrinkage for the treated sites was 23.9% (BAVG). The EBEST estimate of the treatment effect was 53.7% (THETAHEB) whereas the naive, classical estimate, unadjusted for regression-to-the-mean was 73.3% (THETAHF). Thus, the EBEST estimate was substantially closer to the true treatment effect of a 50% reduction having accounted for regression-to-the-mean bias.

Another example was run for the ranking procedure using Texas accident data. Data for this example consisted of accident histories for 254 Texas Counties from 1982-87. All hazardous moving violation accidents and the total county-wide average daily traffic was input. The years 1982-1986 were used to determine the EBEST estimates. The county rankings were then compared based on their expected ranking for accident count and rate and their 1987 observed ranking.

The user has the option to rank by accident count, rate, or both. Both were done in this example. Table 5 lists the top 25 Counties by their 1987 observed accidents (HMVF) and Table 6 lists the top 25 Counties by their observed 1987 accident rate (RATE). The variable LAM and ZHAT are the EBEST posterior estimates for the counties’ rate and count, respectively. At the bottom of Table 6, the EBEST prior parameter estimates are listed. Table 7 is a table of potential accident reduction for each county using the EBEST estimates for various possible percent reductions -.1,.2,.3,.4,.5, and none represented by P1,P2,P3,P4,P5, and zhat, respectively. One of the ways in which this output might be helpful would be the following. Suppose a particular type of safety treatment could be expected to result in a 10% reduction in accidents, P1. If this treatment were to be applied in the 3 counties with the highest accident counts, on our list would promise a reduction of 2293 accidents (1004 + 776 + 513). If this same treatment were applied to the next 20 highest counties, the savings in accidents would be nearly equal to 2263 accidents.

Table 8 gives these same expected numbers of accident reductions but for the 25 Counties with the highest rates. The bottom of the Table gives three counties for which the observed 1987 ranks differed substantially from the EBEST rankings. These were counties 28, 193, and 212. These Counties had exactly the same accident counts in 1987 - 34, and thus were ranked equally on the basis of total accidents, namely 165 out of 254. The EBEST ranking by total accidents differed somewhat for these counties, however. EBEST rankings by expected accident count were 175th, 163rd, and 161st, respectively. However, the observed and EBEST rankings by rate differed substantially for County 213,
namely 18th for the observed and 28th for EBEST, respectively. Figure 7 shows the posterior likelihoods for these counties. Figures 8 and 9 represent the posterior likelihoods for the largest, middle and smallest ranked counties by rate and count, respectively. The difference in these counties is now apparent, they have not only very different means but quite different variances - something which is not taken into account when merely ranking observed values.
## Table 5.

Counties Ranked by 1987 Observed Accident Counts

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### Table 6.

**Counties Ranked by 1987 Observed Accident Rates**

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**EBEST ESTIMATES**

- Prior Rate: 0.036924
- Prior Exposure: 194.74

**DATA**

- Min Acc: 1
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Counties Ranked by EBEST Accident Counts

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Counties Where EBEST and Classical Ranks Disagreed

| Obs Count | 34 | 34 | 34 |
| Exp count | 32 | 36 | 37 |
| Obs Rate  | .0534 | .0228 | .0204 |
| Exp Rate  | .0495 | .0244 | .0228 |
| 10**5 VM  | 637 | 1490 | 1664 |
| Freq Rate Rank | 18 | 190 | 202 |
| EBEST Rate Rank | 28 | 193 | 212 |
| Freq Cnt Rank | 165 | 165 | 165 |
| EBEST Cnt Rank | 175 | 163 | 161 |

VTI RAPPORT 351A
### Counties Ranked by EBEST Accident Rates

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### Counties Where EBEST and Classical Ranks Disagreed

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VTC RAPPORT 351A
Figure 7. Posterior Distributions for Counties where EBEST Ranks Differed

Figure 8. Posterior Distributions for Counties with Highest, Middle and Lowest EBEST Ranks on Rates

Figure 9. Posterior Distributions for Counties with Highest, Middle and Lowest EBEST Ranks on Counts
Summary and Conclusions:

In this study we have presented a method for adjusting for regression-to-the-mean bias in safety measure evaluation. An Empirical Bayes Procedure was developed (EBEST) to adjust for sampling bias. An important data requirement for this procedure is the availability of a reference group.

The reference group and treatment group collectively should represent the entire population from which the treated sites were biasedly selected - that is, the reference group is a sample from the population of potential treatment sites. The reference group can play the role of a classical comparison group, if data is available for the same reference sites during the post-treatment period and the EBEST procedure is used to adjust for any opposite regression-to-the-mean bias which might be reflected in the reference group. Comparison groups as they are classically defined do not typically represent a suitable reference group as they are selected only to represent a time trend and not to represent the population of potential treatment sites.

Another important requirement of the EBEST procedure is exchangeability. Some measure of exposure to accident risk is nearly always necessary to satisfy this assumption. Significant violation of this assumption will result in erroneous conclusions.

The EBEST procedure is a powerful and effective statistical tool for use in safety treatment evaluation. However, it is only as good as the data on which it is based. Given the appropriate data which satisfy the necessary assumption, EBEST is the best statistical method for evaluating a treatment’s true effectiveness.
REFERENCES


Evaluation and Comparison of Traffic Safety on High Standard Rural Roads

Ulrich Brannolte
Dr-Ing
Karlsruhe University
Institute for Transport Studies
Federal Republic of Germany
It is evident that traffic safety on typical rural roads is on average about three times as low as on motorways. But there are different levels of safety on the different types of two-lane roads. In the Federal Republic of Germany there exist two special types of high-standard rural roads: These types of road provide better opportunities for overtakings by means of enlarging the cross-section.

One of these types (b2s) has additional multiple purpose lanes on both sides which can be used temporarily by slower vehicles. The other mentioned variant (b2ü) is an overwide type of rural road. These two types belong to the group of so-called intermediate cross-section roads whose capacity and level of service lies above typical rural roads but below those of the most narrow type of motorways. Intermediate cross-sections are discussed in order to achieve a better safety standard than on rural roads and to avoid some other disadvantages of motorways (mostly environmental aspects).

Intermediate cross-sections are regarded as feasible solutions for traffic loads of about 12000 to 18000 veh/day (AADT).

For a comprehensive investigation of the intermediate cross-section the German Federal Road Research Laboratory has established an expert team, and has initiated various research activities. Extracted from a detailed full-scale accident analysis (some thousands of accidents), which has been carried out by the author, a safety evaluation for the types b2s and b2ü is intended to be represented. The accident features on those types are also compared with those of typical rural roads and those of motorways to show interrelations between these types concerning traffic safety under different road and traffic conditions.
EVALUATION AND COMPARISON OF TRAFFIC SAFETY ON HIGH STANDARD RURAL ROADS
Ulrich Brannolte
Dr.-Ing.
Karlsruhe University, Institute for Transport Studies

1. INTRODUCTION

In the Federal Republic of Germany two-lane undivided rural roads carry about 40% of the traffic in the entire road network. Throughout the past there has been a considerable increase of traffic: The annual average daily traffic (AADT) on federal roads, for instance, increased from 6100 veh/24 hrs in 1975 to 7250 veh/24 hrs in 1985. Federal roads (Bundesstraßen) are trunk roads which serve regional as well as long distance traffic. Like the motorways they are designed, operated, and maintained by federal authorities, but their design is not necessarily subject to freeway (Autobahn) standards. The figures given above are mean values, in the rural road network there are also quite a few sections with traffic volumes so high that dual carriageways should be appropriate. With the AADT still increasing, more and more sections of the network will have to be operated at traffic volumes that high.

As for maximum tolerable traffic volumes, there is an overlapping zone of calculated capacities between two-lane undivided rural roads and dual carriageways, which ranges from AADT values of about 12,000 to about 18,000 veh/24 hrs. Within this range dual carriageways are commonly considered as not always working efficiently, whereas "normal" rural roads have to cope with traffic volumes so high that level of service and road safety are heavily affected. If considered merely under the aspects of road safety, one might well apply dual carriageways to the whole range of traffic volumes in that zone, as it is well known that accident rates on dual carriageways are only about one third of those on two-lane rural roads. However, designing and constructing dual carriageways is increasingly being objected to by the public. These kinds of road require high capital costs and consumption of terrain, and the public usually relates them with particularly bad encroachments upon the environment.

Therefore certain measures for rural roads, which are to provide improved road safety and level of service as compared to ordinary rural roads, have become more and more important. Rural roads suitable for higher traffic volumes are classed with the so-called intermediate cross-sections, which range above the standards of cross-sections for typical rural roads, but below those of typical dual carriageways. Intermediate cross-sections are intended to improve traffic flow and traffic safety while avoiding the disadvantages of dual carriageways or freeways mentioned above.
An expert team at the Federal Road Research Laboratory (Bundesanstalt für Straßenwesen, BASt) is busy surveying research work on all items concerning intermediate cross-sections, and a number of research contracts have already been placed. First results of expert team work may be looked up in BRANNOLTE, DILLING, DURTH et al. (1985).

2. INTERMEDIATE CROSS-SECTION OR HIGH STANDARD RURAL ROADS IN OPERATION

Several rural roads with intermediate cross-sections have been in operation in the Federal Republic of Germany for more than two decades. Some of these types of road are part of the listed regular cross-sections in the respective German guidelines (RAS-Q) of 1982 or their predecessors. The German guidelines for the design and alignment of roads have a modular structure, i.e. each part of them goes into details on a single item of the design and alignment of roads. The respective part (RAS-Q) deals exclusively with properly selecting cross-sections of roads according to their traffic functions. Besides, some other types of road have been realized as non-regular (specially designed) cross-sections which are not part of the guidelines.

A survey of all the intermediate cross-sections included in RAS-Q (1982) was given by BRANNOLTE (1988). It shows how they rank in the guidelines' system of regular cross-sections. There are three basic types of intermediate cross-sections:

- Two-lane dual carriageway with narrowed overall width (c4m type), which is 6 m narrower than the narrowest regular freeway cross-section (b4m type)
- Four-lane undivided road (d4)
- Two-lane undivided rural road with broadened lane width; in this special case multiple purpose lanes additional to two lanes of normal width (b2s)

As the c4m type has carriageways and median, it requires a greater expense of construction work than a two-lane rural road and, therefore, cannot be ranked with high standard rural roads in a narrow sense. To some extent this applies to the d4 type; too. In the following, these types of intermediate cross-sections with either a median or four lanes in total (i.e. two lanes in each direction) shall no longer be dealt with in detail.

Thus the two-lane undivided types of intermediate cross-sections are left as the actual high standard rural roads, namely b2s, b2u and b2+1.

The b2s type is a regular cross-section from the current guidelines RAS-Q (1982). To either side of its roadway there are separate 1.50m-wide multiple purpose lanes which have crossfall and surface identical to the roadway itself. The markings between roadway and the multiple purpose lanes are 0.25m-wide unbroken lines.
As indicated by its name, a multiple purpose lane is good for various functions, e.g. for better protection of "weak" road users (such as pedestrians, cyclists or moped riders), for emergency stops and for service and maintenance vehicles. The main purpose of a multiple purpose lane, however, is to enable overtaking to be done more easily when slower vehicles, if necessary, can move aside for some time while giving way to the faster ones.

Another two-lane undivided type of intermediate cross-sections is the b2ü type ("ü" stands for "überbreit" = overwide): Not being one of the regular cross-sections from RAS-Q, structurally it very much resembles the b2s type. As to tell it from the latter, the b2ü type has no separate multiple purpose lanes but its roadway is composed of two overwide 4.50m-lanes.

The third type is a non-regular cross-section with three lanes, the so-called b2+1 type. The central of its three lanes is alternately assigned to one direction, thus providing two-lane traffic for this direction over a distance of about 1 to 1.5 km.

Rural roads with additional (crawler) lanes at inclines shall not be dealt with here as they are subject to special conditions.

In the Federal Republic of Germany rural roads of the b2s type have been built quite often (in some regions more frequently than in others); and so has the b2s although not being a regular cross-section. Until the year 1983 there were no roads of the b2+1 type in the Federal Republic. In the meantime, a few sections of b2+1 have gone into operation, but they are yet too small a sample for statistical studies and have not been in operation long enough for long-term studies.

Suitable marking provided, all three types of cross-sections mentioned above can be installed on traveled ways on 11m-width or more. Thus, the decision for one out of those types of cross-sections is not so closely linked with constructional aspects as it is for all the other possible types. As for the intermediate types of cross-sections, the decision will be made mainly to the requirements of road users and road safety:

Obviously the b2s type is especially suitable for rural areas with mixed traffic or relatively numerous slow vehicles (e.g. farm tractors, combines etc.). These vehicles will move aside to the multi-purpose lane, thereby reducing the risks of overtaking.

With unbroken lines separating its multi-purpose-lanes from the roadway in a clearly visible manner the b2s type may improve the security of pedestrians and cyclists as well as the optical guidance under bad conditions of visibility.

The b2ü type, however, leaves it to the driver whether to go in the middle of his lane or to move to the extreme right, or how wide the lateral clearance should be when passing another vehicle. The only control is done by the traffic regulations which command every driver to use the right-hand side of the road. Therefore pedestrians and cyclists may subjectively be more exposed to danger on this type of cross-section.
The b2+1 type has traffic ruled in the most definite way: No overtakings are permitted in the single-lane-a-direction sections of the road, whereas overtaking in the two-lane sections of the road is done as if it were a dual carriageway, i.e. without using the lane of the oncoming traffic. The b2+1 thus enables overtaking without regard to oncoming traffic and even without restrictions from slight distances, which may be advantageous if the environment requires a "closely" aligned road. Due to its single-lane-a-direction sections, however, this type of cross-section seems to be not suitable for slow vehicles, cyclists or pedestrians.

A comprehensive analysis of road accident data has been performed to detect relations between the type of cross-section used and the level of safety of the respective road. As there was plenty of statistical data available for b2s and b2u types of cross-sections, the analysis especially comprises a comparison between the two of these.

3. ANALYSIS OF ROAD ACCIDENT DATA

3.1 Selection of Road Sections and Grouping of Accidents

From police records on road accidents data of some selected road sections were inquired, of which accident characteristics could be computed - see BRANNOLTE, SCHWARZMANN (1989). The road sections had to comply with certain preconditions in order to exclude the influence of extreme or singular items of data: Particularly, their AADT had to be at least 7000 veh/24 hrs, they had to be situated outside built-up areas with a minimum length of 3 km, and they must not have inclines steeper than 2%. Every road accident was registered throughout an interval of three years (1984-1986), providing the following sizes of sample for b2s and b2u types of cross-sections:

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The accidents registered were grouped according to various criteria using breakdowns and groupings current in the Federal Republic of Germany as follows: As for accident severity, the worst consequence of an accident puts it into one of the following categories:
Accident with
- serious personal damages = SP
  (including serious injuries and fatalities)
- slight personal damages = LP
- personal damages = PS (in general)
- serious property damage = SS
- slight property damage = LS

Here, fatalities are persons killed instantly or deceased within 30 days after the accident. Serious injuries mean that persons had to be hospitalized for in-patient treatment after the accident. Slight personal damages mean that no hospitalization was required.

The amount of property damage is estimated by the police on the site of the accident: Serious property damage means that damage of at least one party exceeds DM 3,000,-. Slight property damage means that damage of no party exceeds DM 3,000,-. If the number of parties is unknown, an estimated damage of DM 4,500,- is used as a limit for slight property damages.

The type of accident is classified by the different conflicts which led to the event. There are 7 of them:

1) Driving accident (driver loses control over his vehicle)
2) Turning accident (involving vehicles turning left or right from a major road)
3) Turning/crossing accident (involving vehicles turning left or right from a minor road or crossing a major road)
4) Cross-walking accident (involving a pedestrian crossing the road)
5) Parking accident (involving moving vs. stationary or parked vehicles)
6) Progression accident (if not type 1 or 5; involving vehicles moving along in the same direction or oncoming traffic, e.g. rear-end collisions in a queue or head-on collisions)
7) Other accidents (all accidents which cannot be classed with the types 1 to 6)

A further distinction is made according to the moving directions of the vehicles involved in an accident. This generates 10 kinds of accident:

1) Collision with vehicle starting, stopping or parking
2) Collision with vehicle preceding or waiting
3) Collision with vehicle moving along parallelly in the same direction
4) Collision with oncoming vehicle
5) Collision with vehicle turning left or right from minor road or crossing major road
6) Collision of vehicle with pedestrian
7) Collision with obstacle on the road
8) Deviation from the road to the right
9) Deviation from the road to the left
10) Other kind of accident

Eventually, one can distinguish accidents by lighting conditions, weather, state of the road and traffic control.
3.2. Accident Characteristics

In order to rate the accident occurrence numerically, several characteristic figures were calculated both for singular sections and for all road sections of a certain type of cross-section.

For a road section, the accident characteristic most commonly used is the accident rate (UR; referring to vehicle miles):

\[ UR_{ik} = \frac{U_i^k}{DTV \times 365 \times T \times L} \times 10^6 \]  

(1)

in which \( U_i^k \) = number of accidents in group i (e.g. accidents of a certain type) of population k  
(Here: category of accident severity)

\( DTV \) = average annual daily traffic (AADT; veh/24 hrs)

\( L \) = length of road section observed (km)

\( T \) = period of inquiry (years)

\( 10^6 \) = proportional factor for purpose of presentation only

Usually, statistically determined mean costs will be assigned to each different possible consequence of road accidents in order to enable a monetary assessment of accident occurrence: Every accident will "cost" a certain amount of money according to its consequences, and the more exactly this amount can be fitted on prevailing accident structures, the more definite will be the information given by the accident cost rate (UKRk) calculated on the basis of such data.

As experience has shown, accident rates differ from road section to road section, as there may exist special preconditions on any of these. This raises a problem: On the one hand, analyzing the data, of singular road sections will not provide general information; on the other hand, special information on certain types of cross-sections cannot be derived from present global figures (representing e.g. cost structures of all road sections outside built-up areas).

Hence the concept of "adjusted" accident cost rates was devised for personal injury accidents. "Adjusted" means that for each type of cross-section representative costs will be determined, which are especially fitted on the accident structure prevailing in the respective group of data. Those costs (KS) will be calculated for each of the categories of accident severity mentioned above. Provided that the sample size is statistically sufficient, this procedure makes it possible to compare the accident cost structures of the different types of cross-sections.
The following formula is used for the calculation of adjusted accident costs ($KS_i^k$):

$$KS_i^k = \frac{T_i^k \cdot KT + SV_i^k \cdot KSV + LV_i^k \cdot KLV}{U_i^k} + S_k$$

(2)

as for indices $i$ and $k$ see (1); with: $k = 1$: serious injury (SP)

$k = 2$: slight injury (LP)

$k = 3$: personal injury in general (PS),

and: $U_i^k = $ number of accidents

$T_i^k = $ number of persons killed in category $k$

$SV_i^k = $ number of persons seriously injured in category $k$

$LV_i^k = $ number of persons slightly injured in category $k$

whereby: $T_1 = T_3$ and $T_2 = 0$

$SV_1 = SV_3$ and $SV_2 = 0$

$LV_1 + LV_2 = LV_3$

$KT = $ estimated value of a killed person

(here: DM 1,200,000,-)

$KSV = $ value of a serious injury

(here: DM 54,000,-)

$KLV = $ value of a slight injury

(here: DM 4,100,-)

$S_k = $ value of property damages for an accident of category $k$

(here: for personal damage accidents:

$S_1 = $ DM 22,000,-

$S_2 = $ DM 25,000,-

$S_3 = $ DM 24,000,-)

For damage-only accidents the following average values of property damage are used:

$KS_4 = $ 22,000,- (serious)

$KS_5 = $ 5,200,- (slight)

Serious damages are told from slight ones by means of the police records which also include estimations of property damage. Due to their relatively little relevance, property damages will be taken into account only in general by mean values; i.e. there is no further discrimination of $S_1$, $S_2$, $S_3$, and $KS_4$, $KS_5$ as to index $i$.

All the monetary figures given above were taken from a study on the economic benefit of accident prevention: EMDE et al. (1985) determined the average benefit of prevented personal and property damage at the price rates (in DM) of 1985 in the Federal Republic of Germany.
When multiplying the number of accidents from (1) with the adjusted accident costs of personal damage accidents (from (2)) or the general costs of damage-only accidents (KS₄ or KS₅), one will get overall accident costs (UK) as a result:

\[ UK^i_k = U^i_k \times KS^i_k \quad (3) \]

Out of this accident cost rate (UK) can be calculated:

\[ UKR^i_k = \frac{UK^i_k \times 10^3}{DTV \times 365 \times T \times L} \quad (4) \]

(10³ = proportional factor for purpose of presentation only)

According to PFUNDT (1969), p. 17, the accident cost rate of a collection of \( j = 1 \ldots n \) road sections of various length and AADT (UKRZ) will account as:

\[ UKRZ^i_k = \frac{10^3}{365} \sum_{j=1}^{n} \frac{UK^i_{k,j}}{T_j} \sum_{j=1}^{n} DTV_j \times L_j \quad (5) \]

Likewise, the accident rates of a collection of road sections can be calculated by putting into (5) \( U^i_k \), instead of \( UK^i_k \).

4. EVALUATION OF ACCIDENT DATA OF b2s/b2u TYPE ROAD SECTIONS

The present data, which comprise material on types of cross-sections beyond the b2s or b2u type as well, have been subject to results of which are to be given here only in extracts, however, demonstrate the various possibilities of analysis and evaluation, and present the basic results of a comparison between b2s and b2u type road sections.

When it comes to assessing the road safety of a certain type of cross-section, the various types of accidents are of different importance. Here is a breakdown of accidents to the various types of accidents and cross-sections:

<table>
<thead>
<tr>
<th>Type of Accident</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>b2u</td>
<td>36.7</td>
<td>4.8</td>
<td>9.3</td>
<td>0.7</td>
<td>0.6</td>
<td>29.6</td>
<td>18.3</td>
</tr>
<tr>
<td>b2s</td>
<td>25.3</td>
<td>6.9</td>
<td>9.8</td>
<td>0.5</td>
<td>0.6</td>
<td>26.0</td>
<td>30.9</td>
</tr>
</tbody>
</table>
As was to be expected, accidents involving pedestrians crossing the road (type 4 accident) or parked vehicles (type 5 accident) do scarcely happen, but usually cause serious personal injuries (especially type 4 accidents).

The percentage of driving accidents (type 1 accident), and, although not so extreme, of progression accidents (type 6 accident) is relatively higher for the b2ü type or cross-section, whereas the b2s has a higher percentage of unidentified accidents (type 7 accident).

Type 1 and type 6 accidents give the most definite results for the various types of cross-sections. If analyzed together (1+6), the following figures for personal damage accidents (PS) result:

<table>
<thead>
<tr>
<th></th>
<th>URZ</th>
<th>KS</th>
<th>UKRZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>b2ü</td>
<td>0.24</td>
<td>214.400</td>
<td>50.57</td>
</tr>
<tr>
<td>b2s</td>
<td>0.16</td>
<td>247.300</td>
<td>39.64</td>
</tr>
</tbody>
</table>

Accident rates are clearly lower for the b2s, and so are the accident cost rates. However, the costs per accident (all these figures are rounded) are higher than for the b2ü, as on b2s type sections of road there are definitely less, but more serious accidents.

56.3 % of all driving accidents and 28.2 % of all progression accidents on b2ü type sections of road occur in the twilight or during the night. The corresponding figures for b2s type sections are 48.1 and 24.0 %. This indicates better optical guidance on b2s type road sections.

By combining progression accidents (type 6 accident) and collisions with oncoming vehicles (kind of accident No.4), one can filter out typical overtaking accidents: Their percentage of all accidents is 7.5 % on b2s, and 9.2 % on b2ü type road sections. On b2s type sections 66.7 % of all overtaking accidents cause serious personal injuries; on b2ü type sections of road it is 63.2 %.

Turning and turning/crossing accidents (type 2/type 3 accident) are closely related with the traffic and network functions of a certain road section (i.e. number and importance of intersections). An evaluation of such accidents can be done exactly only if their number can be compared with the total number of vehicles having turned from, turned into, or crossed the respective road section. As usual, this number was not available here, so that type 2 and type 3 accidents either had to be omitted or considered separately. Thus a study on all types of accidents except the two of these (1+4+5+6+7) provided the following results for personal damage accidents (PS):

<table>
<thead>
<tr>
<th></th>
<th>URZ</th>
<th>KS</th>
<th>UKRZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>b2ü</td>
<td>0.28</td>
<td>205.700</td>
<td>57.13</td>
</tr>
<tr>
<td>b2s</td>
<td>0.19</td>
<td>242.700</td>
<td>46.31</td>
</tr>
</tbody>
</table>
Again the characteristics UKZ and UKRZ (both referring to vehicle miles) show that the b2s type road sections do better than the b2u sections.

Special consideration of type 2 and type 3 accidents is done by means of adjusted accident cost rates UKRZ:

<table>
<thead>
<tr>
<th>UKRZ (SP)</th>
<th>UKRZ (PS)</th>
<th>UKRZ (LP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b2u</td>
<td>212.300</td>
<td>131.400</td>
</tr>
<tr>
<td>b2s</td>
<td>181.700</td>
<td>108.900</td>
</tr>
</tbody>
</table>

From such figures one can detect significant differences between the various types of cross-sections as to the costs of crossing and crossing/turning accidents. As concerns the figures above it has to be mentioned that an accident of type 2 and of type 3 with serious personal damages costs 14%, and a personal damage accident (in general) costs 17% less on a b2s than on a b2u type road section.

5. GLOBAL DATA AND COMPARISON

For comparisons done more globally, e.g. with other types of cross-sections the data of which cannot be broken down to the various types of accidents, the two main categories of personal damages and serious property damages were combined and provided the following figures:

<table>
<thead>
<tr>
<th>URZ (PS+SS)</th>
<th>UKRZ (PS+SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b2u</td>
<td>0.60</td>
</tr>
<tr>
<td>b2s</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Consequently, as to characteristics referring to vehicle miles the b2s type road sections get the better results throughout. The global costs per accident, however, are statistically higher: This applies especially to accidents with serious injuries, for which the level of costs is about 16% higher with the b2s type of cross-sections.

6. FURTHER WORK

The investigation will be extended to other types of cross-section. Having those results available, what is to be expected within the year 1990, a more comprehensive comparison becomes possible.
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RAS-Q: Richtlinien für die Anlage von Straßen, Teil: Querschnitte, Köln, 1982
Road Design and Safety

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ROAD DESIGN AND SAFETY

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General Background

The road accident problem can be reduced by many different methods and measures. In theory, there are three main methods (ref. 1):

(a) by reducing road traffic;
(b) by reducing the risk of road accidents; and
(c) by reducing the severity and consequences of road accidents.

In practice, these methods can be applied by different measures:

"technical" measures, such as improvements in:

(i) land use;
(ii) road planning, design, maintenance and operation;
(iii) road user education, training and information;
(iv) vehicle design, equipment and inspection;
(v) medical care services;
(vi) traffic legislation, regulations and enforcement; and

"institutional" measures, such as improved:

(vii) coordination of safety activities;
(viii) safety staff education and training;
(ix) funding; and
(x) safety research and development.

To reduce the accident problem in the most efficient way, all these methods and measures should be used. This presentation, however, is focused on the geometric design of rural, two-lane roads and safety. It is mainly based on research results from the Swedish Road and Traffic Research Institute (VTI).

The geometric characteristics of roads affect the risk and the severity of accidents. In order to reduce risks roads should be adapted to the perceptual and behavioural performance of the road users. This means, among other things, that roads should be designed in such a way that sudden elements of surprise are avoided and that information acquisition and decision-making are facilitated. This could, for example, be achieved by sufficient road width, suitable alignment, and good location and design of junctions. It could also be achieved by clearly visible delineation and markings, signs and signals, and good lighting. In order to reduce severity roads should be designed to be "forgiving". This could, for example, be achieved by flat roadsides free from hazardous objects, and by yielding roadside equipment, for instance, lighting columns.

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VTI RAPPORT 351A
Cross-section

The width of the roadway affects the driver's possibilities to manœuvre and to overcome potentially dangerous situations. Narrow lanes and carriageway imply small lateral clearances between overtaking and meeting vehicles, and narrow shoulders means less space for stopped and slow moving vehicles, pedestrians and cyclists, and less margin to regain control and to avoid encroachments into the roadsides. It is, therefore, reasonable to believe that increased lane, shoulder and total roadway width will reduce accidents, unless it results in higher speeds or less attention from the part of the driver. Dual carriageways and motorways with medians will certainly reduce the number of head-on collisions.

Width of Carriageway/Lanes

There are several studies of the relationships between the width of carriageway/lanes and safety (ref. 1). Most results show that accident rates decrease with an increase in width. Some results indicate a rather steep decrease in accidents with increases in width of carriageway from 4 m to 7 m, and that little additional benefit is gained by widening lanes beyond 3.5 m.

Shoulder Width

There are also a number of studies of the safety effects of shoulder widths (ref. 1). Some of the earlier studies indicate that accidents increase with increasing shoulder width. More recent studies, however, show a decrease in accidents with increases in width from 0 m to 2 m, and that little additional benefit is obtained above 2.5 m. It should be observed that it is important that the surface of the shoulders is suitable, and that the level of the shoulders is the same as that of the carriageway.

Roadway Width

There are numerous studies of the relationships between the width of the roadway (carriageway and shoulders) and safety (ref. 1). The results of some Swedish studies for two-lane, rural roads are illustrated in Figure 1. The curves show observed accident rates, expressed as an index with the base (=1.0) at the width of 7 m, for roads of different widths. In general, accident rates tend to decrease with increases in roadway width.
Figure 1. Observed accident rates for different roadway widths, expressed as an index with the base at 7 m.

It should be noted that in most studies it has not been possible to fully eliminate the effects of other safety affecting variables, such as alignment and sight distances, density and design of junctions and access roads, and surface and roadside characteristics. As the standards of these elements often are higher on wide roads than on narrow ones, it is likely that some of the results overestimate the safety effect of roadway width.

It should also be observed that driving speeds tend to be higher on wide roads than on narrow ones, even if speed limits are the same. This means that the curves shown include a component caused by speed differences. These differences may also affect accident severity.

Based on empirical accident data, prediction models have been developed by which accident rates can be estimated for different geometric designs. The model for roads with a 90 km/h speed limit indicates that increases of roadway width, with the same alignment, will reduce accident rates approximately by the factors shown in Table 1 (ref. 3).
Table 1. Accident reduction factors for various increases in roadway width (proportion of the original accident rate).

<table>
<thead>
<tr>
<th>From (m)</th>
<th>To (m)</th>
<th>7</th>
<th>9</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,5</td>
<td>0,10</td>
<td>0,25</td>
<td>0,40</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>0,20</td>
<td>0,35</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>-</td>
<td>0,20</td>
<td></td>
</tr>
</tbody>
</table>

It should be noted that replacing a 13 m wide two-lane road by a 2+2 lanes motorway will reduce accidents by about 50 % (ref. 4).

In a yet unpublished Swedish study it has not been possible to detect any significant differences in accident rates between wide and narrow roads. One reason for this could be that during the last three or four decades narrow roads have been designed with better alignment than before. It is also possible that some modern, wide roads have been given such a smooth alignment, with large radii and only few and short straight sections, that the density of suitable overtaking sections has been reduced, thereby contributing to hazardous overtakings and accidents.

Climbing Lanes

On steep upgrades where overtaking is hazardous, slow-moving trucks can cause considerable delay to fast vehicles. This is often perceived as irritating and can lead to dangerous overtakings and accidents. It is, therefore, likely that special climbing lanes will reduce accidents at such locations.

There are very few studies of the relationships between climbing lanes and safety. One Swedish study indicates that climbing lanes on rural, two-lane roads will reduce the total accident rate, for the section in question, by on the average 25 %, that is, 10 to 20 % on moderate upgrades (3 to 4 %) and 20 to 40 % on steeper grades (ref. 5). It was also observed that additional accident reduction can be obtained within a distance of about 1 km beyond the climbing lane.

Cross Slope and Lateral Uneveness

Flat cross slopes on horizontal road sections will cause water to accumulate on the road surface during heavy rains and can thereby contribute to hydroplaning accidents. Severe unevenness can have similar effects. Sufficient cross slopes and even surfaces are therefore likely to reduce accidents of this type.

There are very few studies of the effects of cross slope on safety. In one study it has been shown that sections with flat cross slopes, in areas with very heavy rainfalls, show higher accident rates than similar sections with steeper slopes (ref. 1).
There are also very few studies of the safety effects of unevenness, such as rutting. In a yet unpublished Nordic study it is indicated that, although hydroplaning accidents on wet surfaces increase due to rutting, the number of other accidents may go down, resulting in unchanged or even possibly lower total accident rates. Plausible reasons are lower speeds on uneven roads and more alert and careful drivers.

**Alignment**

The alignment of a road affects the driver's possibilities to see the road itself, as well as oncoming vehicles and other potentially hazardous objects. Sharp horizontal and vertical curves often implies short sight distances which can contribute to dangerous overtakings and subsequent accidents. Horizontal curves with small radii may also, especially after long straight sections, contribute to skidding, run-off accidents. Steep downgrades can cause problems for heavy vehicles with unsatisfactory brakes. Altogether, therefore, it is very probable that better alignment, with larger radii etc., will reduce accidents, unless it results in higher speeds or less alertness.

On the other hand, it is often argued that very long straight sections can be monotonous and therefore dangerous. It is also plausible that straight sections are worse than smooth alignment with large radii from the point of perception of distance to, and movement of, oncoming vehicles, and movement of the driver's own vehicle.

**Horizontal alignment**

There are several studies of the relationships between horizontal alignment and accidents. The result of a Swedish study is illustrated in Figure 2 (ref. 3).

It can be seen from the figure that accident rates tend to increase sharply for radii under 1,000 m. The curves also indicate somewhat higher rates for straight sections than for sections with large radii.
Figure 2. Predicted accident rates for road sections with different horizontal radii and roadway widths, expressed as an index with the base at radius 1,000 m and width 7 m.

The prediction model developed for roads with a 90 km/h speed limit indicates that increases in radii, all other characteristics alike, will reduce accident rates by the factors shown in Table 2.

Table 2. Accident reduction factors for various increases in horizontal radii (proportion of the original accident rate).

<table>
<thead>
<tr>
<th>To (m)</th>
<th>500</th>
<th>70</th>
<th>1,500</th>
</tr>
</thead>
<tbody>
<tr>
<td>From (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0,25</td>
<td>0,35</td>
<td>0,45</td>
</tr>
<tr>
<td>500</td>
<td>-</td>
<td>0,10</td>
<td>0,30</td>
</tr>
<tr>
<td>700</td>
<td>-</td>
<td>-</td>
<td>0,20</td>
</tr>
</tbody>
</table>

NB! It must be observed that the arc is longer for large radii than for small.

Vertical alignment

It has been shown that steep grades result in higher accident rates. Grades of 2,5 and 4,0 % increase accidents by 10 and 20 % respectively, compared to near horizontal roads (ref. 3).
Sight distance

Short sight distance reduces the driver's possibilities to prepare himself for future, necessary manoeuvres. It is, therefore, very plausible that increased sight distances will reduce accidents, unless it results in higher speeds.

In some studies it has been shown that accident rates decrease with increasing average sight distance, specially for single vehicle accidents in darkness, and that accidents decrease with decreased density of minima for the sight distance (ref. 6).

Roadsides

The characteristics of the roadsides affect the ability to regain control of vehicles which have run off the roadway, and the severity of accidents off the roadway. It is, therefore, very possible that flat side slopes and wide clear zones, free from hard objects, will reduce the number of related accidents and their severity.

The rate of run-off accidents depends, among other things, on:

- road alignment;
- roadway width; and
- roadside design.

The rate increases with decreasing horizontal radius. One study shows that the rate rises sharply with radii less than 600 m for roads with 90 km/h speed limit, and that the rate at 400 m is three times that of a straight section. With a speed limit of 70 km/h the rate rises when the radius comes under 400 m, while, for roads with 50 km/h, the rate does not seem to increase at all (ref. 7). The rate also increases with steeper grades. An increase in grade from 0 to 5 % can be followed by a run-off accident increase of 60 to 70 %.

The risk of running off decreases with increased roadway width. An increase from 7 to 13 m roadway can be expected to reduce run-off accidents by 40 to 50 %.

There are very few studies of the effects of roadside design on accident rates. In one study it has been shown that accidents increase significantly with steeper side slopes and lack of clear zones (ref. 1).

The severity of run-off accidents depends mainly on:

- roadside design (front and back slopes, ditches);
- lateral distance to objects, clear zones; and
- crash characteristics of roadside objects.

There are few accident studies of the relationships between roadside design and accident severity. It has, however, been shown that the severity depends mainly on the gradient and the length of the side slope (ref. 1).
In lack of accident statistics, computer simulation has been used to evaluate the effects on severity of various slope and ditch configurations. Some Swedish studies (ref. 8) have shown that for soil cuttings the following front/back slope combinations: (i) 1:6/1:6 and further out 1:2; and (ii) 1:4/1:4 and further out 1:2; are considerably safer, especially for vehicles departing at high speeds and large angles, than: (iii) 1:6/1:2; (iv) 1:3/1:3 and further out 1:2; and (v) 1:3/1:2. If the costs of average run-off accidents for combinations (i) and (ii), which showed similar results, were set at 1 (index scale), the cost of an accident for (v) was estimated at about 3.5.

The same studies indicate that embankments slopes of 1:6 and 1:4 are safer than 1:4 and further out 1:2, 1:3 and 1:2. The difference between 1:4 and 1:3, however, was small, while the difference between 1:3 and 1:2 was substantial. Expressed in the same cost scale as before, the accident costs for 1:4 and 1:3 were estimated at about 0.7, while the cost for 1:2 was around 1.7. Embankments with ditches at the bottom (back slope 1:2) turned out to be hazardous.

For rock cuttings the lateral distance from the edge of the roadway to the rock wall is of great importance for the severity. Front and back slopes of 1:6 and 1:6 respectively and a distance of 6 m from the roadway to the wall turned out to be insufficient to prevent a rock collision for a 90 km/h and 20° departure. In another study 6.5 m was sufficient to avoid a rock collision for 90 km/h and 12°, while 4.5 m was sufficient for 90 km/h and 3°, but not for 7°. Expressed in the same cost scale as before, the average accident cost for flat slopes and 2.5 m distance to the wall was estimated at 5 to 6, while the costs for 4.5 m and 6.5 m were about 2.5 and 1 respectively. It is also clear that there should be a transition between the back slope and the rock wall, for example, in 1:2.

To design the roadsides, and to take potentially hazardous objects into consideration, it is necessary to know how far from the road departing vehicles stop. Therefore, numerous studies have been carried out to establish the lateral distance between the edge of the roadway and the position either where the vehicle struck an object or where it stopped of other reasons. The results indicate that a clear zone of 7 to 11 m for vehicles leaving the roadway at large angles and high front slopes, and 4.5 to 7 m for small angles and low front slopes, would be sufficient in most cases.

There are many different types of roadside objects which can be hit by departing vehicles. Besides side slopes, the most frequent collision objects are: trees; poles (electricity, telephone and lighting); and guardrails. The severity of the collisions depends on the crash characteristics of the objects and the distance between the road and the object. Collisions with trees, rocks, bridge columns, abutment ends and similar objects are normally very severe, and this is also often the case with pole and culvert collisions. Even guardrail collisions can in many cases be quite severe.
In some studies the accident costs for collisions with different objects have been estimated. The results show that, expressed in the same cost scale as before, collisions with trees, poles and guardrails are about 6 to 8, 3 to 4 and 2 to 4 respectively (the guardrails were of a semi-rigid, nonblocked W-beam type, often with concrete posts).

**Junctions**

Junctions are specially hazardous spots in a road network because they imply many potential conflicts between crossing, diverging and merging traffic streams. Junctions, where drivers have to observe, and control, many possible conflict areas at the same time may be more prone to accidents than junctions where the drivers can focus their interest first on a few conflict areas and then on the next ones etc. Therefore, it seems reasonable to believe that junctions with islands and special lanes for turning vehicles and similar types of channelisation will reduce accidents.

On the other hand, it is possible that junctions with very complicated designs and large conflict areas may be more dangerous than those which are simple to perceive and understand.

There are numerous studies of the relationships between junction design and accidents. The results of some Swedish studies for rural junctions are presented in the following (ref. 9).

The number of accidents at junctions of a certain type depends mainly on the volume and distribution of traffic on the primary and secondary roads. Using empirical accident data, prediction models have been developed, see Figure 3 and 4, by which the accident rate can be estimated as a function of the total incoming traffic and the proportion of traffic on the secondary road.
Figure 3. Predicted accident rates (accidents per 10^6 incoming vehicles) for 3-way, rural junctions.

Figure 4. Predicted accident rates (accidents per 10^6 incoming vehicles) for 4-way, rural junctions.
From the figures it can be seen that an increased percentage of traffic on the secondary road increases the accident rate. No similar, clear relationships have been found between injury consequence (number of killed and injured persons per accident) and traffic volume and distribution.

It has been shown that accident rates are, on the average, 1.5 to 2 times higher for 4-way junctions than for 3-way junctions with the same traffic volume and distribution. In addition, it has been shown that the injury consequence is about 1.5 times as great for 4-way junctions as for 3-way junctions. Altogether, therefore, it is often advantageous to replace 4-way junctions by two staggered 3-way junctions.

Some results concerning different junction designs, or safety measures, are summarized in Table 3.

Table 3. Changes in accidents and injury consequence for different geometric designs at rural junctions.

<table>
<thead>
<tr>
<th>Design/Measure</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accidents</td>
</tr>
<tr>
<td>Island in secondary road</td>
<td></td>
</tr>
<tr>
<td>* 3-way</td>
<td>0</td>
</tr>
<tr>
<td>* 4-way</td>
<td>-10</td>
</tr>
<tr>
<td>Left-turn lane in primary road, raised, kerbstone, island</td>
<td></td>
</tr>
<tr>
<td>* 3-way</td>
<td>0</td>
</tr>
<tr>
<td>* 4-way</td>
<td>-10</td>
</tr>
<tr>
<td>Left-turn lane in primary road, painted island</td>
<td></td>
</tr>
<tr>
<td>* 3-way</td>
<td>-20</td>
</tr>
<tr>
<td>* 4-way</td>
<td>-10</td>
</tr>
<tr>
<td>Roundabout</td>
<td>0</td>
</tr>
<tr>
<td>Grade separation</td>
<td></td>
</tr>
<tr>
<td>* 3-way</td>
<td>-10</td>
</tr>
<tr>
<td>* 4-way</td>
<td>-50</td>
</tr>
</tbody>
</table>

Traffic islands in the secondary road have been shown to reduce accidents at 4-way junctions by some 10%, while it does not seem to have any significant effect at 3-way junctions.

The safety effects of left-turn lanes on the primary road seem to depend on whether the channelisation is achieved by raised kerbstones or by road markings. Kerbstone channelisation has turned out to be a doubtful measure, at least in rural areas and for 3-way junctions. In many cases kerbstone islands seem to lead to more severe accidents, specially in 4-way junctions. Painted
channelisation, on the other hand, has proved effective at 3-way junctions in rural areas, the number of accidents falling by about 20 %. The effect at 4-way junctions seems to be smaller, about 10 %.

At 4-way junctions in semi-urban areas, with a high percentage of secondary road traffic, roundabouts have proved to be very effective, as they will reduce injury consequences by some 50 %.

Grade separation is certainly a very effective option, as it reduces both accidents and injuries per accident by about 50 %, at least at 4-way junctions.

It should furthermore be observed that there are many other safety measures which can be efficient in junctions, for example, speed limits, yield and stop regulations, and traffic signals.

**Summary**

Research results have shown the following for rural, two-lane roads:

1. Increased **width** of carriageway/lanes, shoulders and roadway, up to certain limits, normally reduces accident rates. It must be observed, however, that it has hardly ever been possible to fully eliminate the effects of other safety affecting variables, and that many results therefore probably overestimate the safety effect of increased width.

2. **Horizontal radii** under 1 000 m increase accident rates. The rate for a curve with a 400 m radius is about 50 % higher than for one with a 1 000 m radius. Steep **grades** also increase accidents. 4 % grades show 20 % higher rates than near horizontal sections.

3. Road sections with short **sight distances** show higher accident rates than sections with long sight distances.

4. **Roadsides** are very important to road safety. Front and back slopes should preferably be 1:4 or flatter. In rock cuttings the distance from the edge of the roadway to the rock wall should be at least 6 to 9 m on high speed roads and 4 to 6 m on low speed roads. Clear zones, free from hazardous objects, should be sufficiently wide to avoid most collisions, that is, 7 to 11 m on high speed roads and 4.5 to 7 m on low speed roads. Hazardous objects should be eliminated or located outside the clear zone.

5. **Junctions** are specially dangerous spots in a road network. It is often advantageous to replace 4-way junctions by two staggered 3-way junctions. Islands in secondary road have a small positive safety effect. Left-turn lanes in primary road are favourable, at least if they are produced by road markings, and specially at 3-way junctions. Roundabouts and grade separation are very effective options from the safety point of view.
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2. Brüde U: Statistical description of the relationships between accidents and road and traffic variables, VTI Meddelande 13, 1976 (In Swedish).


Future Highway Safety Program

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presented by

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Office of Highway Safety
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A Strategic Transportation Research Study for Highway Safety

There is a need for a fresh look at various programs designed to increase the safety of our nation's highways. Very large amounts of effort and money are spent each year in major safety initiatives such as the revision of State motor vehicle laws, improvements to licensing and administrative procedures, increased emphasis on traffic enforcement and adjudication, better recordkeeping and communication regarding the problem driver, and public information and education efforts designed to modify human behavior. Considerable funds are also devoted to safety programs involving vehicle inspection; emergency medical services; driver training and education; vehicle design; and highway design, construction, maintenance, and rehabilitation.

The Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHSTA) have forwarded a proposal to the Transportation Research Board (TRB) to conduct a strategic highway safety research study. The proposed study will focus on all aspects of the driver, vehicle, and roadway systems which affect highway safety. The emphasis will be on topics and areas where Federal, State, and local governments are currently spending their limited resources in efforts to improve highway safety. This study will ask the questions — What are the major highway safety problems today and what will they be tomorrow? What existing or new safety initiatives have the highest potential of substantially reducing deaths/injuries on the Nation's highways in a cost-effective manner?

This paper will review the current status of a strategic research study on highway safety which focuses on all aspects of the driver, vehicle and roadway systems which affect highway safety. Accidents data will be reviewed and areas where key research is needed will be identified. The overall highway accident problem will be compared with all accidents and with other national health research programs to add perspective to the tragedy of highway accidents.

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1. INTRODUCTION

This paper presents information on recent national highway safety activities in the United States. The future of the highway safety program and the direction of highway safety research and development is currently under considerable discussion. A summary of the major activities is provided. Information is also provided on a strategic research study on highway safety jointly sponsored by the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA).

The size of the U.S. highway transportation system is enormous. Data from 1987 indicates that we had 161,818,000 licensed drivers operating a fleet of 183,930,000 registered vehicles on a roadway system of 3.9 million miles.

Almost 1,924 billion vehicle miles were traveled on the system in 1987.

1.1 FATALITY TRENDS

Two common statistics are used widely to report highway fatality data. Highway officials generally use the number of fatalities per 100 million vehicle miles traveled (VMT). Health officials generally use the number of fatalities per 100,000 population. Figure 1 shows both statistics.

The fatality rate based on VMT shows a steady decline from about 5.0 in 1960 to 2.5 in 1986 (2.4 in 1987). This statistic clearly indicates that safety on our nation's highways is improving. This is the transportation perspective.

The fatality rate based on population has declined slightly from 20.2 in 1960 to 19.1 in 1986 (19.1 in 1987), but there is no clear downward trend. In fact, the public health perspective is that the fatality rate per 100,000 population has remained fairly constant since 1982.
The number of fatalities per year is another widely used statistic to describe highway fatalities. Figure 2 shows comparable trends for the number of fatally injured victims in traffic accidents. Unlike the fatality rate based on population, the number of annual traffic fatalities has increased from 36,399 in 1960 to 46,056 people killed on the Nation's highways during 1986 (46,385 in 1987). Are 46,000 fatalities per year an acceptable price for the type of mobility enjoyed in the United States?
2. **CRASH LOSSES**

Recent work by Viner provides some insight on the nature and the costs of the current traffic safety problem in the United States. In Table 1, total 1985 highway accident losses are shown in terms of the first harmful event in the accident. The category "collision with motor vehicle" applies to those accidents that involve two or more vehicles. A "Collision with fixed object" occurs when the vehicle leaves the roadway and includes such things as collisions with utility poles, guardrail, trees, etc. A "Collision with non-occupant" primarily involves pedestrians and bicyclists. "Non-collision" fatalities are generally the result of vehicle rollovers. A "Collision with non-fixed object" includes items such as collisions with trains at railroad grade crossings.
### Table 1. 1985 Highway accident losses (2)

<table>
<thead>
<tr>
<th>First Harmful Event</th>
<th>Fatalities</th>
<th>Injuries</th>
<th>PDO Vehicles</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Cost</td>
<td>Number</td>
<td>Cost</td>
</tr>
<tr>
<td></td>
<td>(1,000,000's)</td>
<td>(1,000,000's)</td>
<td>(1,000,000's)</td>
<td>(1,000,000's)</td>
</tr>
<tr>
<td>Collision with motor vehicle</td>
<td>18,315</td>
<td>$23,036</td>
<td>2,292,000</td>
<td>$25,091</td>
</tr>
<tr>
<td>Collision with fixed object</td>
<td>12,250</td>
<td>$23,541</td>
<td>591,000</td>
<td>$6,578</td>
</tr>
<tr>
<td>Collision with non-occupant</td>
<td>7,419</td>
<td>$10,923</td>
<td>181,000</td>
<td>$1,991</td>
</tr>
<tr>
<td>Non-collision</td>
<td>4,363</td>
<td>$6,131</td>
<td>186,100</td>
<td>$1,240</td>
</tr>
<tr>
<td>Collision with non-fixed object</td>
<td>1,478</td>
<td>$2,108</td>
<td>113,300</td>
<td>$290</td>
</tr>
<tr>
<td>Total</td>
<td>43,825</td>
<td>$65,738</td>
<td>3,363,400</td>
<td>$36,997</td>
</tr>
</tbody>
</table>

The first harmful events are listed in column 1 in order of descending number of fatalities reported in the Fatal Accident Reporting System (FARS) data. Columns 2 and 3 list the number of fatalities and the societal cost of the fatalities.

The number of injuries and the number of vehicles involved in property damage only (PDO) accidents are estimates based on the National Accident Sampling System (NASS) data. Columns 4 and 5 list the number of injuries and the societal costs of these injuries. Columns 6 and 7 list the number of PDO crashes and the societal cost of the crashes.

The costs of the crashes in Table 1 are based on the rational investment cost estimating research of Miller using estimates of what people are willing to pay for improved safety. In June 1988, the FHWA recommended this approach to estimating accidents costs for use in economic analysis of highway projects. The cost figures in Table 1 are based on the following individual costs:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatality</td>
<td>$1,500,000</td>
</tr>
<tr>
<td>Injury</td>
<td>$11,000</td>
</tr>
<tr>
<td>Vehicle in a PDO accident</td>
<td>$2,000</td>
</tr>
</tbody>
</table>

Table 2. Costs of traffic accidents

Using these figures, the costs of police reported traffic accidents in 1985 (FARS and NASS data combined), is estimated to be $115 billion. Fifty-seven percent of these losses are attributable to fatal accidents, 32 percent to injury crashes and the remaining 11 percent to property damage only.

In terms of the first harmful event, one half of the total cost is incurred from collisions with motor vehicles. Thirty percent of the loss is in the collisions with fixed objects. Ten percent of the loss occurs from collisions with pedestrians, cyclist, etc. Seven percent of the total loss results from non-collision rollover fatalities. Three percent of the loss involves such accidents as collisions with trains and parked cars.

Actual highway travel increased 4 percent in 1985. If this trend continues, and if the fatality rate of 2.5 per 100 million miles driven, the injury rate of 188 injuries per 100 million miles driven, and the PDO rate of 374 per 100 million miles driven remain constant, the annual deaths on the highways could reach 80,000 by the year 2000. Moreover, the number of injuries could reach 6,000,000 and
the number of PDO could reach 12,000,000. If this occurred, societal cost would double by the year 2000. Is this acceptable? Will it happen?

2.1 PERSON YEARS OF LIFE LOST

In "Injury in America" a comparison is made between years of potential life lost due to injury, heart disease, cancer and all other diseases.\(^{(5)}\) This comparison is shown in figure 4. However, the figure has been modified to show the years of life lost due to motor vehicle fatalities. The 1.7 million years of life lost were calculated using 1986 data from FARS.

Based on the information, one could easily conclude that in terms of the years of life lost, traffic accidents are as serious a health threat as cancer and heart disease. In terms of the societal costs, the costs of motor vehicle accidents are staggering.
3. SAFETY PROGRAM PROPOSED BY OTHERS

The development of a national, measurable highway safety program is an enormous undertaking that challenges the creative abilities of those involved. Such opportunities do not occur often for a variety of political, institutional and budgetary constraints. Fortunately, the opportunity is here today and there has been a series of meetings related to the development of a future highway safety program. The results of these activities are summarized below.

1. Strategy session on highway safety priorities held in Orlando, Florida, June 1987. (6)

The participants at the Orlando meeting were nationally recognized experts in their respective fields and were selected because of their concern about highway safety. Their goal was to identify realistic, workable traffic safety measures for the nation. The Automotive Safety Foundation and the Highway User Federation have used the results of this conference to launch a campaign entitled "1.5 by 2000." Their aim is to reduce traffic fatalities to 1.5 fatalities per 100 million VMT by the year 2000. Their publication "Highway Safety Priorities to the Year 2000" contains the recommendations from the national strategy session which should allow the nation to achieve "1.5 by 2000". (5) The major recommendations were:

- Safety belt use laws in all states and 70 percent compliance in States with belt laws by 1990.
- Education programs to inform the public on the use and benefits of passive restraints and manual seat belts.
- Suspension of administrative license for alcohol related offenses.
- Expansion of alcohol education programs to reduce drunk driving.
- Increased enforcement of traffic laws.
- Implementation of laws requiring motorcycle helmet use.
- Uniform licensing for commercial motor vehicle operators.
- Improvement of commercial motor vehicle operator training.
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- Improvement of roadway signing, marking and delineation, and hazard elimination.
- Uniform data collection and analysis to facilitate problems identification and progress assessment.

The publication contains numerous other suggestions, but the ones listed above are most critical. Of these, implementation of the first four are crucial to the success of the campaign. Basically, all of the above recommendations involve the implementation of existing technology.

2. A total of 65 public forums conducted by the Advisory Committee on Highway Policy held in the United States from August 1987 to May 1988.(7)

In early 1987, the American Association of State Highway and Transportation Officials (AASHTO) initiated the Transportation 2020 Program. The goals of the program are to assess the Nation’s surface transportation needs through the year 2020, to evaluate alternatives for meeting those needs, and to develop agreement through a national consensus on the best long-term program with specific, realistic goals and measurable results. As a part of the Transportation 2020 Program, 65 public forums were held between August 1987 and May 1988. The people at the forums were largely transportation users voicing their opinion on future highway programs. Listed below are some proposals by transportation users that were voiced at many of the meetings.(6)

- Safety belt use laws must be expanded and enforced.
- Drunk and drugged driving countermeasures must be strengthened.
- State and community safety grants should continue.
- Safety needs of bicycle users should be met and bicyclists should share in their costs.
- Federal funding for safety improvements to highways should continue.
- "Larger/smaller" motor vehicle conflicts must be addressed.
- Federal role in financing and assuring compliance with motor carrier regulations of vehicles and drivers should continue.
- Funding for traffic safety enforcement should increase.
- Improved signing and other safety needs of older drivers must be

This conference dealt with specific highway issues related to the roadway environment. The purpose of the conference was to: (1) assess effectiveness of the highway safety program over the past twenty years; (2) compare the highway safety program to other national health and safety programs; (3) examine political process and issues in allocating public funds among safety and non-safety related programs; (4) examine appropriateness of using benefit to cost procedures in allocating public funds; and (5) present plans to advance highway safety to the year 2010.

Papers were presented by twenty nationally recognized experts and leaders in various fields related to highway safety. While all of the papers provided insights into different aspects of the highway safety area, the insights presented in "Plans and Programming for Highway Safety to the Year 2010" are especially appropriate. The results are summarized below:

- Establish a national goal to reduce the annual number of traffic injury and fatal accidents below the 1985 level; and secure commitment to this goal at the National, State and local levels.

- Develop an affordable plan to achieve the highway safety goal by selecting and upgrading portions of the 3.8 million mile system.

- Incorporate explicit safety requirements into major programs such as reduction of traffic congestion and RRR.

- Establish mainstream safety organizations at Federal and State agencies with resources and clout to organize and administer highway traffic safety programs.

- Increase the highway technical community's awareness and accountability of highway safety problems by establishing formal training university and on-the-job training programs and instituting, at appropriate levels, systematic and periodic dialogue between individuals involved in highway accident investigation, design and standards, maintenance, operations and legal issues.

- Insure on a continuing basis that all highway safety programs and efforts are effective and cost efficient by developing and using quantitative and objective in-service appraisal of safety policies, techniques, technology, and nationally accepted protocol that evaluate the relative merit of societal benefits and costs of health and safety activities.
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- Continue efforts to develop and implement new safety technology that addresses changing conditions such as increased traffic volume, smaller cars, increased numbers of truck, aging drivers, etc., and strive for a coordinated and integrated effort from the highway, automobile, and driver factions.

- Incorporate state-of-the-art technology in communications, training, and mass media techniques to enhance safety technology transfer.

4. Summer meeting of Committee on Planning and Administration of Transportation Safety held in Annapolis, Maryland, August 29-31, 1988.

At the summer meeting of TRB Committee A1A05, papers were presented in four areas: driver, vehicle, highway environment, and traffic records. Priority issues were identified for each area, and a priority listing was developed based on the combined issues. A partial listing of the major issues are listed below in priority order:

- Establish a user financed highway safety fund.
- Conduct a Strategic Transportation Research Study for Highway Safety.
- Establish a national traffic records center, including information and technology transfer.
- Review driver licensing and post-licensing control.
- Enhance coordination and cooperation of transportation professionals.
- Provide training for highway safety professionals.
- Determine feasibility of highway design and vehicle design to provide highway-vehicle transport systems that maximize mobility and safety.

3.1 COMMON RECOMMENDATIONS

There were common highway safety recommendations from all of the meetings especially in the areas of seat belts, alcohol, and driver education. Are the recommendations practical? What costs are involved in implementing the recommendations? What are the benefits? Who has the responsibility for specific recommendations? What sort of driver, vehicle, roadway interaction will occur in the future? Will technology evolve to the point where a fail-safe roadway environment is possible? Will the crashworthiness of the vehicle
increase to the point where traffic barrier systems are no longer needed? All of these are issues that must be addressed during the development of a national safety program.

4. START AT THE BEGINNING

While it is possible to develop a future highway safety program based on these recommendations, it would be a mistake to do so. Over the years, a number of programs at the Federal, State and local level have evolved as various spending programs have been developed. Many of these programs have become so institutionalized that they are difficult to change. There is a need for a fresh look at various programs designed to increase the safety of our Nation's highways. Much effort and money are spent each year in major safety initiatives such as the revision of State motor vehicles laws, improvements to licensing and administrative procedures, increased emphasis on traffic enforcement and adjudication (especially regarding the alcohol-impaired driver), better recordkeeping and communication regarding the problem driver, and public information and education efforts designed to modify driver behavior. Considerable funds also are devoted to safety programs involving vehicle inspection: emergency medical services; driver training and education; vehicle design; and highway design, construction, maintenance, and rehabilitation. A new national highway safety program must start with the basic driver, vehicle, roadway interaction and proceed from that point.

The driver is a key element in highway safety. It is the driver's responsibility to operate the vehicle in a safe manner. Educating, licensing, and enforcing of driver compliance with traffic laws are key State responsibilities. How much do these activities affect highway safety? Are they cost-effective from a safety standpoint? Are they directed at a known problem? How can human behavior be modified to improve highway safety?

The motor vehicle continues to change. Passenger cars are lighter and more pickups and vans are entering the vehicle fleet. Longer and heavier large trucks are using many of the Nation's routes. Passive restraints and anti-lock brakes are beginning to be incorporated into new vehicles and will improve highway safety. Efforts are being made to increase the crashworthiness of the motor vehicle. Development of the motor vehicle has been the primary concern of the private sector, but there are numerous Federal regulations. Are major safety features being ignored? Are vehicle safety decisions based on cost effectiveness?
The roadway environment has improved significantly in the past 20 years. Efforts continue to improve edge markings and signing; remove roadside obstacles; and to install crashworthy guardrails. Although State highway agencies have the ultimate responsibility for the design and construction of highways, the Federal government is also involved. Is the current highway research directed at the critical safety problems? Are highway design features based upon safety data? Are major safety features being ignored because of cost tradeoffs or funding limitations?

Fortunately, a national effort to identify highway safety research needs in the U.S. is underway.

5. A STRATEGIC TRANSPORTATION RESEARCH STUDY FOR HIGHWAY SAFETY

The Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHSTA) have recently signed a contract with the Transportation Research Board (TRB) to conduct a strategic highway safety research study. The study will focus on all aspects of the driver, vehicle, and roadway systems that affect highway safety. The emphasis will be on topics and areas where Federal, State, and local governments currently spend their limited resources in efforts to improve highway safety. This study will ask the questions:

• What are the major highway safety problems today and what will they be tomorrow?
• What existing or new safety initiatives have the highest potential of substantially reducing deaths/injuries on the Nation's highways in a cost-effective manner?

Current programs will be examined to determine whether there is evidence that they are effective in reducing highway fatalities and accidents. Ineffective initiatives will be re-examined to see if they can be improved before additional capital outlays are made. The study will identify problem areas where major capital outlays for intensive research effort offer the most promise for the development of programs that can significantly reduce highway accidents.

The TRB will involve technical experts and sufficient Government and industry leaders to review and evaluate highway safety research needed to define those areas that have the highest potential for improving the productivity and/or effectiveness of current safety efforts. In addition, new initiatives that offer
substantial promise to reduce deaths and injuries will be evaluated. The TRB will develop criteria to be used to:

- Define the major highway safety problem areas.
- Understand current administrative organizations involved in highway safety, the nature of their present safety efforts, and where the majority of funds relating to highway safety activities are being spent.
- Evaluate the effectiveness of these current programs.
- Identify research needs.
- Estimate research cost, duration, likelihood of success, and potential benefits.
- Develop a strategic priority research agenda for improving highway safety.
References


