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Safety Standards for Road Design and Redesign
SAFESTAR

FINAL REPORT

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Coordinator: SWOV Institute for Road Safety Research, Leidschendam NL

Partners:

- TNO Human Factors Research Institute; Soesterberg, NL
- RD Road Directorate; Copenhagen, DK
- VTI Swedish National Road and Transport Research Institute; Linköping, S
- VTT Technical Research Centre of Finland; Espoo, FIN
- LNEC Laboratório Nacional de Engenharia Civil; Lisbon, P
- NTUA National Technical University of Athens; Athens, GR
- CETE Centre d'Etudes Techniques de l'Équipement Normandie Centre; Grand-Quévilly, F
- CDV Transport Research Centre; Brno, CZ

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SAFESTAR

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ABSTRACT

SAFESTAR was a research study focusing on traffic safety for what is known as the 'Trans-European Roadway Network' (TERN) that links the major European centres. The knowledge needed for being able to carry out an effective safety policy at the European level is insufficient in regard to various safety aspects of road infrastructure. SAFESTAR was established to fill in these gaps of knowledge, with special notice being given to the following seven topics: emergency lanes and shoulders along motorways, tunnels located on motorways, express roads, cross-sections of rural roads, curves in rural roads, major junctions on roads in urban areas, and assessing the safety of road infrastructure during the planning and design stages (the performing of safety audits).

Within the scope of SAFESTAR, the investigation into these areas pays much attention to the differences between design standards as they now exist or are being developed in the individual countries within Europe. Of particular interest are the differences between the countries participating in SAFESTAR: the Netherlands, Denmark, Sweden, Finland, France, Portugal, Greece and the Czech Republic.

- SAFESTAR is providing an overview of the nature and the degree of danger in the emergency lanes and shoulders of European motorways. Next, an inventory and analysis are being made of the various measures currently taken to correct these problems. Finally, the study goes deeper into the criteria for applying various kinds of safety provisions such as safety barriers.
- SAFESTAR will select a tunnel design deemed responsible by expert opinion. Next, this tunnel design will be tested in a driving simulator.
- SAFESTAR is charting the dangers of express roads and in doing so, analyses the reasons for choosing this type of road. Attention is also given to the future development of express roads: will the problem disappear due to the construction of additional (semi-)motorways, or on the contrary, will the situation worsen due to the increasing amount of traffic? Finally, recommendations are being provided for road design and for the circumstances under which these roads should be constructed.
- The cross-section of a road determines to a great extent which traffic situations can occur on such a road and also which accidents can occur. SAFESTAR evaluates the difference in cross-sections based on the characteristics of the accidents. A few promising corrective measures are being selected, and the effects of these are being studied with test subjects driving vehicles equipped with test devices.
- Another task of SAFESTAR is to increase knowledge in the effect that the design of curves has on the safety of rural roads. The evaluation is based on two methods: by using calculation models for the speed profile and accident frequency, and by investigating driving behaviour immediately before and in curves when using different kinds of marking and signing.
- For designing urban junctions, it would be desirable to have a calculation model which would predict accident levels that will occur once the junction is built or put back into use after modifications. These calculation models already exist, but they still require a great deal of improvement. SAFESTAR focuses on obtaining an improved calculation model.
- The aim of safety audits is to assess the pre-construction safety level of road infrastructure design. A design can be assessed in various phases of the design process. Teams

of experts not directly involved in the project carry out the audits. SAFESTAR will evaluate existing audits procedures and will test a number of different procedures in different countries.

The findings produced by SAFESTAR will be compiled to create a coherent list accompanied by recommendations concerning the safety aspects of road design.

EXECUTIVE SUMMARY

The level of road safety is, to a large extent, determined by the features and layout of the road transport system infrastructure. If the human errors which result in accidents are to be held in check then proper road design is crucial. It has been estimated that improvements in the engineering of roads has been one of the main factors behind the reduction in casualties on the roads of EU countries in recent years.

To achieve their full effect safety principles in road design have to be applied in a systematic and consistent manner. Progress towards the optimal adaptation of road design to these principles is expected to produce a considerable reduction in the number of accidents and accident rates compared to the existing situation in Europe.

Standards play a vital role in road design. Not all countries have a full range of design standards applied to their road networks and this situation contributes to the size of the road safety problem on the continent as a whole. Continued improvement of road design standards on the Trans European Road Network (TERN) is required and this will help to install good practise on all types of road throughout Europe.

Proposals and agreed technical standards, however, cannot be expected to flow simply from a safety perspective. The overall objective of the SAFESTAR programme has been the formulation of *safety arguments* for selecting particular design elements or dimensions for inclusion in the improvement and augmentation of design standards.

The safety arguments produced in the course of this study do not lend themselves to summary and simplification. They are laid out, section by section, in the main body of this report. The standards derived from them are listed, for convenience, in Section II. However, a number of themes, flowing from the work, are discussed briefly below on a topic by topic basis.

The list of standards in Section II cannot be considered complete because the research reviewed and carried out for the project could not fill all the gaps in our present knowledge. A second list indicating where more data and research are required can be found in Section III.

Hard shoulders (Emergency lanes) on motorways

Currently, there is a safety problem because of the design of hard shoulders and the presence of obstructions on or adjacent to them. SAFESTAR has provided an overview of the nature and degree of danger on hard shoulders. Current measures taken to combat the problem have been reviewed and analysed.

Criteria have been generated for the application of safety barriers and other measures.

Tunnels on motorways

Frequently the dimensions and design standards of tunnels do not match those of the adjacent stretches of motorway and this has resulted in problems. SAFESTAR has selected a number of tunnel designs intended to reduce problems and has tested these designs by means of driving simulators.

Express Roads

The current infrequent application of this type of road on TERN is expected to increase significantly in the near future. Because it caters for long distance and local traffic it is known to be relatively unsafe. SAFESTAR has catalogued the dangers and analysed the reasons for the choice of this type of road, forecasting developments and recommending standards of design, and a basis for the choice.

Rural Roads

Currently about one third of the length of TERN is comprised of this type of road which is known to generate the vast majority of injury accidents outside built-up areas. SAFESTAR has carried out evaluations and looked at research on the different effects of corrective measures and a variety of marking and signing with reference to cross-sections and to the design of curves.

SAFESTAR has developed improved calculation models which make it possible to assess curve designs for safety aspects before the roads are constructed.

Major Urban Junctions

A large number of designs and design methods for dealing with these junctions is already available. There is a need for improvements to the process of choice of design with reference to the safety of all road users including cyclists and pedestrians. SAFESTAR has focused on obtaining improved calculation models.

Road Safety Audits

The principles and practise of Road safety Audits (RSA) are seen as an excellent tool for improving safety through the careful monitoring of design by independent experts. Some European countries already have procedures for carrying out RSA. As part of SAFESTAR, these procedures have been described and compared. RSA also appears to offer an opportunity to promote consistency in design standards. (see Section I)

I. RECOMMENDATIONS

I.1 Recommendations for the European Commission (DG VII/Transport)

- The European Commission should sponsor a pilot scheme of Road Safety Audits (RSA) on construction and upgrading on TERN roads. It should also act as broker for the development of a widely acceptable protocol for RSA which should include standards and procedures. The protocol should also state the requirements for, and the responsibilities of the audit team.
- The communication and dissemination of knowledge about the safety aspects of road design are a pre-requisite for obtaining a (sustainably) safe road network. The Commission should play a central role in the creation of the tools and the channels to achieve this on a pan-European basis.
- The Commission should organise the preparation of a code of good practise for the design of roads in the Trans European Road Network.
- Although there has been some progress in the creation of pan-European research and data-logging it is important that future design and regulation does not depend on the compilation of the findings of disparate research projects. The Commission should actively stimulate co-operation in research to a level where it will support policy and design standards across Europe.

I.2 Recommendations for National governments (Departments of Transport)

- National goals for the improvement of road safety should be set as an essential element of road safety policy
- The appropriate resources to facilitate the achievement of these goals should then be assigned to Road Authorities, those responsible for design guidelines and manuals and Research Institutes working in this field. This should include budgets, laws, regulations, organisation and the provision of tools for the design of roads.
- The development of Road Safety Audit procedures and methods should be stimulated and the results applied in practise.

I.3 Recommendations for Road authorities and those responsible for manuals and guidelines on road design

- Three basic design principles should be adhered to:
 - The road system should be classified into types with different design standards
 - Design should seek to prevent situations in which large differences in speed, mass and direction are present simultaneously.
 - Design should facilitate the predictability of behaviour in traffic situations.
- At a national level the principles and practise of Road Safety Audit should be integrated into the design and construction process as a tool for improving road safety.
- The new safety standards and procedures derived in this research should be applied to road schemes and incorporated in manuals and guidelines. (see Section II)

I.4 Recommendations for Research Institutes

- National road research institutes should evaluate Road Safety Audit both with reference to results obtained in the actual application of the technique and the potential for savings to flow from its general application in the design process.
- Efforts should be made to improve the involvement in cross-national and pan-European research to support the creation of a full range of European policies and standards.
- When planning research programmes, reference should be made to the list of new and additional research requirements which is included in this report (Section III).

II. NEW SAFETY STANDARDS SUGGESTED BY THIS RESEARCH

In this list the new standards are organised by road type for convenience. Within the main body of this report they are organised by topic in Sections 2.1 to 6.2. where they appear alongside discussion of the research from which they are derived and the reasons why they are recommended.

II.1 Motorways

The design of motorways should incorporate the following:

- An obstacle-free zones at least 9 metres wide on each side of the carriageway. (see Section 4.1)
- Any inclines within these obstacle-free zone should not be steeper than 1 in 5 (20%) for slopes with a total height of more than 5 metres. Where the total height is 2 metres or less the slope should not be steeper than 1 in 6 (17%). (see Section 4.1)
- The median strip should have a width of at least 20 metres except where an appropriate safety barrier is used. (see Section 4.1)
- Where sections of hard shoulder (emergency lane) are identified as having a greater than normal risk of accidents they should be improved by an increase in width, the application of a rumble strip, or an improvement in lighting. (see Section 3.1)
- Where tunnels are used, the road layout within the tunnel should not be allowed to exert too much influence locally on the road user's choice of speed (for example, the sudden disappearance of the hard shoulder (emergency lane) will have a substantial influence on the choice of speed). (see Section 5.1)
- At exits and entries situated within a tunnel the road user should always have a clear view forward of at least 100 metres. (see Section 5.1)

II.2 Express roads

The design of express roads should incorporate the following:

- Use should be restricted to high-speed motorised traffic. (see Section 3.2)
- The frequency of access and exit should be restricted. (see Section 3.2)
- Vertical alignment over the brow of a hill (convex curve) should be such that the forward view should never be less than the distance required to stop safely. (see Section 2.1.1)

- Vertical alignment through a dip or hollow (concave curve) should have a minimum radius of 3,000 m. (see Section 2.1.1)
- The lane width on both single and dual carriageways should be 3.5 m. (see Section 3.2)
- The cross-section of the carriageway should include a continuation of the paved area beyond the edge of the traffic lanes. (see Section 3.2)
- The median strip should have a width of at least 20 metres except where an appropriate safety barrier is used. (see Section 4.1)
- Where a safety barrier is used in a median strip a recovery zone should be used between the barrier and the traffic lanes. It should be wide enough to allow the recovery of vehicles to take place. (see Section 4.1)
- The median strip should be free from slopes and obstacles. (see Section 4.1)
- Where a single carriageway road climbs a significant incline a crawler lane (climbing lane) should be included on the uphill side of the road. (see Section 3.2)
- Cuttings and embankments alongside the carriageway should not be steeper than 1 in 5 (20%). (see Section 4.1)

II.3 Single carriageway rural roads

The design of single carriageway rural roads should incorporate the following

- A lane width of 3.5 metres. (see Section 3.3)
- Shoulders on each side of the traffic lanes to a width of 1.3 to 1.5 metres, giving a total carriageway width of approximately 10 metres. (see Section 3.3)
- Cuttings and embankments alongside the carriageway which are not steeper than 1 in 5 (20%). (see Section 3.3)
- Obstacle-free zones extending for at least 3 metres on each side of the carriageway. (see Section 3.3)
- The horizontal alignment of the road should remain consistent (as defined in Section 2.1.2).
- Road marking and signing within curves based on the strategy tested in SAFESTAR. (see Section 2.2.1)

- Poor perception of a curve during both approach and negotiation should be prevented by improved marking and signing and by cutting back vegetation which might obscure the view. (see Section 2.2.1)
- Amelioration of the speed at which a curve is entered by various devices. (see Section 2.2.1)
- Avoidance or the reduction of consequences where a vehicle leaves the road by the use of hard shoulders, safety barriers, and high friction surfacing. (see Section 2.2.1)
- The reduction of head-on collisions by the use of ghost islands and hard shoulders. (see Section 2.2.1)

II.4 Major urban junctions

The design of major urban junctions should incorporate the following:

- A clear view for an adequate distance for all road users regardless of weather conditions or time of day. (see Section 6.2)
- A maximum speed differential between road users of 30 km/h. (see Section 6.2)
- A choice of junction type to maximise the effect of accident reduction. (see Table 6.10)
- The arrangement of traffic streams so as to avoid as far as possible compromising the visibility and the prediction of the behaviour of road users. (see Section 6.2)

III. AREAS WHERE MORE RESEARCH OR DATA ARE REQUIRED

III.1 Motorways

- Within the SAFESTAR project itself some of the design characteristics of long tunnels have been investigated, including the width of the hard shoulder (emergency lane), patterns on the walls and ceiling, and exits and entries within the tunnel. Other characteristics remain to be investigated:
lighting conditions, lane widths, curves, slopes, restriction of sight distances, and the variation in traffic volumes.
- The accident risk on the hard shoulder (emergency lane) can only be established with reference to data about the number of accidents and the level of exposure to risk. There is a need for these data to be collected which is not currently being fulfilled.
- Safety barriers of various types are available. More work is needed on the comparative cost-effectiveness of the different types.
- Barrier testing should also be carried out with regard to impacts by heavy vehicles and particularly by those with a higher than average centre of gravity.

III.2 Express roads

- If express roads continue to exist as a separate class within the road network more work will be required on the comparative safety of motorways, express roads and other inter-urban roads.
- There is a need to identify which safety measures will improve safety on express roads without generating a false expectation of adherence to motorway standards.
- What long term strategy and level of standards will produce an economically acceptable level of cost-effectiveness for governments and authorities dealing with express roads?

III.3 Single carriageway rural roads

- The design of these roads can currently be supported by the use of speed and accident models but they are in need of considerable improvement. The current data need augmentation and refinement and the variables modelled and range of application need to be extended and better defined.
- The effectiveness and availability of alternative methods of separating opposing traffic streams and avoiding accidents where vehicles leave the road is another area which need more work.

III.4 Major urban junctions

- Although a great deal of experience has informed the current design of major urban junctions there is a need for more investigative work with regard to cyclists and pedestrians especially in terms of behaviour, conflicts and accidents.
- The design of junctions can be supported by accident models. However, these models still need a great deal of improvement with regard to the data (number and type of junctions, number and type of accidents), the model structure (type of variables), and the specifications for the range of application (which design elements, which stage of the design, which type of junction, which country).

1. INTRODUCTION

1.1 Design philosophy

Designing roads is a profession which needs different kinds of skills. First of all one uses the traffic engineering techniques. Secondly one uses notions about driver behaviour, how road users react on the road and its environment. And last but not least, one is guided by a design philosophy. This philosophy can be implicit, formed by intuition and experience, or it can be explicit, developed by research and evaluations. SAFESTAR prefers to enhance an explicit design philosophy. In fact a combination of two philosophies: ‘sustainably safe traffic and transport system’ and ‘relation design’. Both philosophies are described in this report.

1.1.1. *The concept of a ‘sustainably safe’ traffic and transport system*

The Dutch concept of a sustainably safe traffic and transport system (STTS) has far-reaching ambitions. The Dutch national government has set a goal of 50% fewer road traffic fatalities and 40% fewer casualties by the year 2010, (taking the figures for 1985 as the baseline). Because these aims go further than merely following an existing trend, a sustainably safe traffic system with structurally low accident figures has to be found. An important component of such a system is a sustainably safe design for the Dutch road network in which roads are divided into a limited number of classes. Each class has a clear and unambiguous function for traffic and must be easily distinguishable from the other classes.

Road safety must become an integral element of the entire Dutch road network (both urban and rural). It is inevitable that this will have major consequences for urban and regional planning and for traffic systems planning.

Starting-points

The STTS begins with four starting-points:

- Man is the yardstick for each technical system
- Adapt the traffic and transport system to man
- Prevent failures
- If failures do occur, then minimize the consequences

Principles

The STTS gives a new meaning to the old man-vehicle-road model:

- The road infrastructure should be adapted to human capabilities and shortcomings
- The vehicles should simplify the driving task and should offer protection
- The road users should be well-informed and, where necessary, be controlled

Design principles

The design principles in STTS aim at connecting the three angles of the triangle FUNCTION-DESIGN-USE (*the golden triangle*): The transportation plan prescribes a certain function for a road, mostly as a result from an origin-destination analysis. The traffic engineer applies this function for his design. In this design he makes assumptions about the behaviour of the future road users (intended use). Finally, after the opening of the road, the actual use of the road will

show if traffic behaviour and traffic volumes agree with the original function and design. If not, the design can be altered or the use and/or behaviour can be adapted.

In some cases the use which was not intended, can result in rather satisfactory situations. In that case the road users managed to deal with the situation. And in other cases the actual use can be as intended but after all, not satisfactory. These discrepancies need special attention and can teach us something more about the relations between Function-Design-Use.

Furthermore STTS wants to stimulate the interaction between the road environment and the driving task. STTS triggers this interaction by combining unique combinations of road elements in each road class.

Three design principles have been established:

- A functionally planned road network: each link fits well into the whole system and actual route choice is in accordance with planned route choice.
- A homogeneous use of the road: road users should only be confronted with small differences in speed and mass.
- A recognizable road environment which stimulates the right expectations: predictability of traffic situations.

Traffic and transport functions

Each traffic and transport system is meant to:

- interconnect areas
- distribute within an area
- give access to 'individual' destinations (houses, schools, shops etc.)

Of course these functions also exist in, and have to be met by, STTS.

Functional road classification

The road classification in a sustainably safe road network differs from usual road classification systems. The traditional road classification systems accept that each road can have different functions at the same time. In STTS each road will get one and only one function, so the number of classes is the same as the number of functions:

I **Interconnective roads** are only meant to interconnect areas.

II **Distributors** are only meant to distribute traffic within an area.

III **Access roads** are only meant to give access to individual destinations.

A road with a certain function should be fully adapted to that function and all elements which belong to other functions should be removed or separated.

Requirements

The design of the road network should meet certain requirements in order to fulfill the starting-points and principles of STTS. These requirements are of two types: functional and operational. The functional requirements can be regarded as the basic criteria for dividing the roads of the network into the various classes. For each of the roads thus given a specific class, there are also operational requirements. These concern the most important characteristics of the cross-section, the alignment, the types of traffic (car, bike, moped, pedestrian) allowed to use the road and their position on the cross-section. Both functional and operational requirements should be included in the existing guidelines for urban and rural roads.

Functional requirements

The functional requirements for the road network are as follows:

- largest possible areas with traffic-calming (both in rural and in urban area);
- a maximal part of the journey using relatively safe roads and routes;
- journeys as short as possible;
- the quickest and shortest routes to coincide;
- avoid the necessity to search for directions/destination;
- easily recognizable road classes;
- limit and make uniform the number of possible types of design;
- avoid encountering oncoming traffic;
- avoid encountering traffic crossing the road being used;
- separate types of traffic;
- reduce speed at potential points of conflict;
- avoid obstacles near the carriageway.

These twelve functional requirements apply to all road classes in the entire urban and rural road network

Operational requirements

The operational requirements have been formulated in such a way that the design specifications can be the next step. However, the operational requirements offer many opportunities for the designer to vary the road design according to the local demands or according to his own preferences. The operational requirements must ensure that the differences between the road classes are bigger than the differences within the road classes. Table 1.1 shows these requirements.

Predictibility

A small set of the fore-going operational requirements should ensure the predictability of the traffic situations. These set comprises continuous longitudinal road elements:

- marking
- separation of directions
- pavement, irregularity of the surface
- obstacle-free zone

The mechanism which ensures the right predictability consists of two steps: at first the road users must be able to recognize the road class by these four elements. Secondly, through information and experience, the road user knows which possible traffic situations belong to the present road class.

This mechanism tries to lower the workload (or mental load) of the driver. This will have a positive influence on the performance of the driving task.

Workload

In addition to the general effect of the operational requirements on the workload, the designer can optimize the workload by other road elements. Messer et al. (1981) have developed a procedure to evaluate the effect of the road and road environment in the stage of the design.

| | Type of area | | | | |
|--|----------------------|-----------------------------|----------------------------------|-----------------------------|--------------|
| | Rural area | | | Urban area | |
| Road class | Interconnecting Road | Distributor | Access Road | Distributor | Access Road |
| Abbreviation | IR | D | AR | D | AR |
| Speed limit (km/h) | 120/100 | 80 | 60 | 50 | 30 or less |
| Marking (longitudinal) | fully | fully but different from IR | partly | fully but different from IR | no |
| Physical separation of directions (number of lanes in one direction) | yes (1 or more) | yes (1 or more) | no (1) | yes (1 or more) | no (1) |
| Type of physical separation | barrier | difficult to cross | n.a. | difficult to cross | n.a. |
| Emergency facility | lane | shoulder or lay-by | no | shoulder or lay-by | no |
| Pavement, surface irregularity | minor | minor | major | minor | major |
| Accesses | no | no | yes | no | yes |
| Crossing (mid-block / between junctions) | grade separated | grade separated | at grade | grade separated | at grade |
| Parking | no | parking lane | carriageway | parking lane | carriageway |
| Public transport: stops | no | turnout | carriageway | turnout | carriageway |
| Obstacle-free zone | large | medium | small | medium | (very) small |
| Cyclists on the carriageway | no | no | depending on the local situation | no | yes |
| Mopedists on the carriageway | no | no | yes | yes | yes |
| Slow moving motorized vehicles (e.g. agricultural vehicles) | no | no | yes | yes | yes |
| Speed reducing facilities (e.g. humps) | no | no | yes | occasionally | yes |
| Lighting | to be decided | | | | |

Source: CROW (1997)

Table 1.1 *Operational requirements for five different road classes in STTS*

In their view the workload value of a certain feature is the result of:

- sight distance
- expectation
- unfamiliarity
- workload of preceding feature
- workload potential rating for the present feature

The potential rating is based on expert opinions.

Krammes & Glascock (1992) showed a relationship between this workload value and the accident risk.

1.1.2. *Relation design*

Lamm & Smith (1994) define 'relation design' as follows:

“..... no more single design elements with minimum or maximum limiting values are put together more or less arbitrarily; rather, design element sequences are formed in which the design elements following one another are subject to specific relations or relation ranges.”

This approach should result in a longitudinal profile which offers the car driver a consistent chain of tangents and curves. The consistency is focussed on the sight distances and design speeds of the successive design elements.

The definition of design speed is subject to discussion. Some countries (United States, Belgium) define design speed as the maximum speed at which car drivers can use the road safely and comfortably, a sort of target.

Other countries (Germany) accept that drivers mostly drive faster than the design speed.

Therefore these countries define the design speed as the speed which is only exceeded by 15% of the drivers (V_{85}). This second approach demands insight in the actual speeds which will occur. Quantitative relationships have been developed to assist this insight (e.g. Lamm & Choueiri, 1987).

Some countries (United Kingdom, Australia) use combinations of both definitions.

Each of these approaches demands a specific procedure to reach a satisfactory relation design. In the United States the relation design is less developed because their definition of design speed related to each design element, results in a sequence of elements which are not very well attached to one another. Leisch & Leisch (1977) elaborated a method to determine the speed profile of a road. For each curve the designer determines the safe entering speed. This speed is confronted with the speed that can be attained by the acceleration in the preceding tangent, e.g. a curve after a long tangent will be entered with a higher speed than a curve directly after an opposite curve. The speed profile shows the discrepancies between the safe speed and the most likely speed.

The speed profile is set up for both directions, because the driving speed is depending on the sequence of curves and tangents a driver will meet.

The point of the Leisch & Leisch method is that the difference between two successive entering speeds should never exceed 15 km/h. This value is based upon the experience that drivers are able to control such a speed reduction and upon an accident analysis of Glennon & Joyner (1969).

In Germany the Kurvigkeit or Curvature-change-rate (CCR) is used to derive the V_{85} . One calculates the absolute sum of curvature change rates in the horizontal alignment (in gon/km²) including transition curves. The relationship between the calculated sum and V_{85} can be found in the German design guidelines. This relationship was based on empirical research (Köppel & Bock, 1979). In a good design two successive elements are not allowed to show differences in speed exceeding 10 km/h (first condition). A second condition concerns the curve radii of two successive curves. These radii should be designed according to a relationship which was reported by Lippold (1996).

Both approaches, from Germany and from the United States, have their characteristic procedures, but Lamm et al. (1986) showed that, when both methods are applied to the same road, the outcome will be more or less the same.

Lamm et al. (1994) promote a slightly different procedure to reach a good design consistency. Their method uses three criteria:

- The difference in the V_{85} of two successive design elements should not be greater than a certain value (10 km/h in a 'good' design and between 10 and 20 km/h in a 'fair' design).
- The difference between V_{85} and the design speed should not be greater than a certain value (10 km/h in a 'good' design and between 10 and 20 km/h in a 'fair' design) and at the same time the radii of two successive curves should be of the same size.
- The difference between assumed and actual demanded side friction should not exceed a certain value (a positive value in a 'good' design and between -0,02 and 0 in a 'fair' design).

The application of these criteria can be supported by introducing an evaluation module which checks each design alternative.

1.2 Road Safety Audits

This section describes tools and procedures established in different countries which conduct Road Safety Audits (RSA). These RSAs are utilized to identify potential safety problems and concentrate on safety measures to overcome these problems. This technique is used to detect possible safety hazards, in the various stages of a scheme, before a new road is open to traffic. The slogan '*Prevention is better than cure*' is already well known to us, and Road Safety Auditing can establish an association with road safety. The application of this *preventive* technique can prevent accidents or reduce the severity of accidents. Except for minimizing trauma, and increasing the designer's awareness of road safety, RSAs can also reduce the overall lifetime cost of a scheme, for it is less likely that *remedial* rebuilding of road sections should take place. Therefore this report deals with schemes subject to design and redesign of new roads, rather than existing roads.

Strict applying of design regulations does not always lead to a safe road, for general rules don't always fit correctly to specific situations. When applying a RSA, it improves awareness of road safety, and highlights safety among other aspects of road design.

Road Safety Audits' roots

In use since the early 80's, RSAs have been established as a requirement in construction and maintenance of highway schemes in the United Kingdom . In the UK, RSA is compulsory for all trunk roads and is also issued on a voluntary basis in other road schemes. There are many years of experience with RSA and many countries which have developed (or which are developing a RSA system) have looked carefully to the UK. Another country which has a long history concerning road safety is the USA. In the USA a method exists called 'Safety Reviews'. This Federal Highway Administration method is less formalised than the UK Department of Transport method and also emphasises more the incorporation of guidelines and compliance with standards rather than the use of checklists and road user behaviour. On non-FHWA roads sometimes the local road authority conducts an informal check.

Over the years the evolution of auditing process has been dynamic. The idea behind safety audits and the scope remain the same. Since safety audits were introduced, however, experience gained from practice has been used to improve the procedures.

Objectives of safety audit as pointed out in Great Britain

The main objective of safety audits is to ensure that highway schemes operate as safely as possible, i.e. to minimise the number and severity of accidents occurring. This can be achieved by avoiding accident-producing elements and by providing with suitable accident-reducing elements. The purpose of safety audits is to ensure that 'mistakes' are not built into new schemes.

Other specific aims of the Road Safety Audit are :

- to minimise accident risk on the network adjacent to new schemes
- lay emphasis on safe design practice and increase the awareness of everyone involved in planning, design, construction and maintenance of roads.
- to highlight the importance of taking into consideration the needs of all types of users
- to reduce the whole-life cost of the schemes, by minimising the need of future corrections.

In order for a safety audit to be successful, certain factors should be taken into consideration. The key factors that contribute to the efficiency of the safety audit may refer to the organisation and the selection of the audit team:

With respect to safety audit organisation, support and commitment of senior management is essential. Safety audits should be an integral part of an agency's overall program. Local authorities often use a Road Safety Plan as a framework in which the RSA is placed. By doing so, the RSA is part of the overall safety management strategy.

Undertaking the road safety audit, a procedure

A RSA procedure does not differ very much between different countries. Their procedures have many similarities with the procedure used in the UK:

1. Collection of information. Such information may include: detailed plans, design standards, traffic volumes, pedestrian counts, and accident records. At this stage, prior to any appraisal of the layout, a discussion with the design team about the objectives of the design, is advisable.
2. The systematic and detailed check of the design follows. However, different countries use different numbers and names of stages. The UK Department of Transport Trunk roads auditing only requires stage 1-3, the other UK stages are used by different Counties and the IHT.

| Number of stages used. | | | | | | | | | |
|------------------------|--------------------------|---------|----------------------------|--------|---|-----------|-----------------|-------------|--------------------|
| United Kingdom | | Denmark | | Norway | | Australia | | New Zealand | |
| F | Feasibility | 1 | Initial design | 1 | Planning | 1 | Feasibility | 1 | Feasibility |
| 1 | Preliminary design | 2 | Preliminary design | 2 | Details | 2 | Draft design | 2 | Project assessment |
| 2 | Detailed design | 3 | Detailed design | 3 | Construction work | 3 | Detailed design | 3 | Final design |
| 3 | Prior opening | 4 | Opening | 4 | Prior opening | 4 | Pre opening | 4 | Pre opening |
| 4 | Post opening | 5 | Monitoring (Existing road) | 5 | Post opening road marking / maintenance | 5 | Existing road | 5 | Existing roads |
| 5 | Maintenance / monitoring | | | | | | | | |

At Stage 2 this often involves overlaying the details from one plan on to another, as there will be different drawings for road layout, street-lighting, safety fences, signs and markings. It is often the interaction of features that causes problems - for example, no one intends that lamp columns should be erected on the wrong side of safety fences. For stages 1 and 2, following up a preliminary assessment of the design, it is essential that a site visit is carried out, so that the tie-in with existing roads can be considered, and the local conditions assessed. For stage 3, examination of the physical elements in site is the main task at this stage of the process. This may involve negotiating the scheme from different directions, in the dark, and under adverse weather conditions.

In examining and evaluating the design, checking each element individually is one aspect. Once the audit team has predicted the type of accident problem that is likely to be associated with an aspect of the design, a known remedy to mitigate that problem should be suggested. It is important that the scheme viewed as whole and the impact of the combination of its elements and features to the users, is taken into account.

In undertaking this task, the use of checklists is strongly recommended.

3. The findings of the audit are presented in a formal audit report. A precise description of the possible problems identified is required, giving reasons for the anticipated conditions. For the purpose of strengthening the arguments and ensuring the objectiveness of the results, it is required that the auditors make use of control data and the guidelines. The final audit report should also include recommendations on how to solve the problem. Location plans on which identified problems are referenced, and drawings for presenting the proposed amendments, can be used.

When recommending, it should be kept in mind that the objective of the audit is the improvement of the suggested scheme and that contradicting the designer and questioning/changing the relevance of the design, is not desirable. Within the local situation it is likely that the safety audit team will discuss their findings with the design team, possibly with an informal report. This is not the case on a Road Safety Audit for the Department of Transport where a formal audit report is required to be produced, and sent to the Department direct.

Monitoring

The use of monitoring and evaluation is a method by which road safety auditors can learn about certain issues affecting the scheme, which can be applied to similar projects and areas elsewhere. Feedback to the designers could lead to more awareness of the implications of their design to safety. Nevertheless the Dept. of Transport HA 42/92 says: "It is central to the auditing procedures that the Audit Team have no connection with the scheme design and should

maintain that their views are not influenced by familiarity or from natural 'pride of authorship'. Providing safety advice by the AT to the design team conflicts with the importance of independence. However, many respondents to the questionnaires think this kind of information is more important than perfect independence. Training for all participants in road safety audit, including staff members, could increase the awareness and importance of safety issues. Another way of training the design team is providing them with checklists. By doing so, the audit team knows which items the audit team will take notice of. Some 'evident' mistakes could be prevented from being incorporated in the design. This does not make the Road Safety Audit obsolete, this rather gives the AT more time to use their experience and intuition.

Some British Counties use a Road Safety Unit which is monitoring safety, and collects all accident information (quote: 'this keeps you rolling', motivated) directly from the police. For monitoring e.g. Nottinghamshire, there is also a close link between the police and the Accident Investigation Bureau. Roads which have been audited at the last stage, are monitored for one year, and after that period they are evaluated. Monitoring seems to be necessary because one designs for its use, but the usage changes, so the design probably should also change. Monitoring in the consultancy branch is poor, probably the result of a lack of willingness.

Checklists

The purpose of the checklists is to insure that nothing is overlooked. Practitioners should not rely solely on them and are encouraged to expand them. Over the past few years checklists were re-considered and the new checklists in the revised guidelines are meant to indicate 'principal issues' rather than provide detailed lists of the items to be examined. Different checklists are provided for each safety audit stage. Checklists appear to be not *very* important. The usage of checklists decreases as the knowledge of Road Safety Audits increases.

Auditing existing roads

Road safety audits refer mainly to new designs. They can however be implemented to existing roads as a complementary tool together with the analysis based on accident data. One of the main purposes when auditing existing roads is to identify if elements and features are in accordance with the standards indicated by the hierarchy within the network.

Some elements summarised and compared

SAFESTAR has highlighted some countries using Road Safety Audits (Van der Kooi et al., 1998). In this section the differences and similarities between RSAs in those countries are summarised. France and the USA do not have an explicit RSA system and thus are not mentioned in this overview.

Definitions used in various countries

The definitions used by the different countries are more or less the same. They all concentrate on road safety as one separate aspect of road use/design. The various definitions are summarized below. It should be mentioned that the definitions regarding Denmark and Norway are of course translations.

UK:

A formal procedure for assessing accident potential and safety performance in the provision of new road schemes, and schemes for the improvement and maintenance of existing roads.

source: Guidelines for The Safety Audit Of Highways, IHT (1996)

Denmark:

Road Safety Audit is a systematic and independent assessment of the safety aspects of road schemes. Its purpose is to make new and reconstructed roads as safe as possible - before construction is started and before accidents occur.

source: Manual of Road Safety Audit, RD (1997)

Norway:

A systematic and independent evaluation which ensures that the products (roads, traffic systems, traffic control) have the quality desired with respect to road safety. The audit should not primarily control whether the planning is in agreement with traffic regulations, but should also be concerned with the auditor's knowledge and assessment techniques and implementing of the check list.

source: Road safety in the scheme - inspection and audit of plans. 1996

Australia:

A road safety audit is a formal examination of an existing or future road or traffic project, or any project which interacts with road users, in which an independent, qualified examiner reports on the project's accident potential and safety performance.

source: Road Safety Audit 1994

New Zealand:

A formalised process to identify potential safety problems for road users and others, and to ensure that measures to eliminate or reduce the problems are considered fully. A safety problem is defined as a feature which has been identified from a drivers perspective which gives a misleading or confusing message.

source: Safety audit policy and procedures 1993

Status

Only in the UK is the RSA mandatory for all trunk roads. In New Zealand, a RSA is mandatory on a 20% sample of new state highway projects. The status on other type of roads and in the other countries is 'recommended'.

| Mandatory RSA | | | | |
|----------------|--------|---------|-----------|----------------------------------|
| United Kingdom | Norway | Denmark | Australia | New Zealand |
| ✓ | | | | ✓ (20% sample of state highways) |

Types of road

There are different types of road for which a RSA is issued. These types are Rural (motorways, express roads or trunk roads) and Urban roads. Another differentiating element is whether a proposed scheme of an existing road undergoing a RSA is known or unknown to the Audit

Team. When the scheme subject to auditing is part of a periodical (or even annual) maintenance program it is more likely that the scheme is ‘known’ to the Audit Team. The Norwegian AT to be formed will probably consist of a group of county officials auditing a scheme from one of its members.

| Type of Road subject to be audited | | | | | |
|------------------------------------|-------------------|-------------|-------------|-----------------------------|---|
| | United Kingdom | Denmark | Norway | Australia | New Zealand |
| Motorway, Trunk road or Urban road | Rural Urban | Rural Urban | Motor Trunk | Rural Urban | Rural Urban |
| Known or Unknown | Known and Unknown | Unknown | (Known) | AT should have ‘fresh eyes’ | AT should be ‘not regular users’ in the case of a stage 5 audit |

Procedures

The initiator of a RSA project, the one who ‘starts’ the Audit, as well as the one who is finally responsible, i.e. decides whether or not to implement solutions to ‘the remarks’ made by the Audit Team, are mentioned below. The number in this table refers to the paragraph which describes the procedure of the Audit. Also added in this table is, whether the results of a RSA are open to the general public. Norway and Denmark have not discussed the item in depth yet. In Denmark a general rule exists providing the general public access to documents produced in or at behalf of the public administration. In the UK and Australia RSAs could be used in court cases. In New Zealand some audits become evidence in so called planning courts who decide whether a (usually contentious) project will proceed. The last row in this table indicates whether there is discussion between the auditors and designers regarding the RSA results.

| Initiator, Person finally responsible, Organisation, Public Access, and Discussion. | | | | | | |
|---|--------------------------------|-------------|----------|--------------------------------|-------------------------------|--------------|
| | United Kingdom | | Denmark | Norway | Australia | New Zealand |
| Initiator | Project Manager | | Designer | Road Chief | Designer / Client | Client |
| Person finally responsible | Client | | Client | Road Chief / Department Leader | Designer / Client | Client |
| Organisation | 2.3.2 | | 3.5.2 | 4.4 | 5.3 | 6.3 |
| Public Access | available at Public Inquiries* | | Yes | Pilot not accessible | available at Public Inquiries | some |
| Discussion | Dep.of Transport | Possible ** | Possible | Not necessary | Yes, with Designer or Client | Not intended |
| | consultant | sometimes | | | | |
| | Various Counties | Yes | | | | |

* source: HA 42/94 Vol.5 Sec.2.2

** source: HA 42/94 Vol.5 Sec.2.29-30.

The Audit Team, quantifications

Independence is important in road safety auditing. Yet there are many different ways to ensure this independence, and even within some countries there are differences. An Audit Team could for example come from inside or outside the ‘designer’s organisation’. The capability and the number of people in an AT also differ from project to project. The AT can even contain trainees. The qualifications / experience of the audit team do not vary much between the countries. It has been found that a RSA could be carried out by one person, but in most cases more personnel is recommended. The New Zealand’s audits of existing roads tend to be quite large; four members.

Qualifications of the auditor

Experience in design and implementation, designing remedial measures, and knowledge of accident figures, are highly desirable. Furthermore, the auditor should have knowledge of road safety in general, design standards, road user behaviour and road safety measures in general. Experience with accident investigation techniques is a must for an auditor. It is also important to know what is going on in the designer’s world, and stick to known practice.

The police assistance is used in stage 3, thus most of the time only minor modifications are made by them. It is preferable to ask them to join in at stage 2, but this seems to be difficult to arrange. Training courses are necessary to pick up problems, but not enough on their own; one also needs experience. Two members of staff can also join in the team and one person always visits the site at daytime and at night.

| Independence, Size, and Qualifications. | | | |
|---|---|--------|--|
| United Kingdom | DoT: outside the organisation, other cases: less strict. | 1 - 7 | DoT: Accident investigation Road Safety engineering |
| Denmark | Independent, can be from inside or outside the same organisation as the designer. | 1 - .. | Traffic accident reduction and accident analysis. Common knowledge of designing and construction work. |
| Norway | Independent, can be from Road Directorate, neighbouring counties, the same county, or consultant. | 1 - .. | Knowledge of traffic safety, and the actual project. |
| Australia | AT from outside the organisation, or another design team, or the designer himself. | 1 - .. | Accident investigation, traffic engineering, traffic management, design, human perception. |
| New Zealand | Independent, but they could have a staff member involved in the auditing | 1 - .. | Different skills and experience |

Other elements with respect to the auditing team are:

- The team should include specialised safety engineers with experience in accident investigation and analysis.
- In order to ensure that the procedure is as objective as possible, the auditors should be independent of the design team. This is insisted on by the Department of Transport.
- Attention should be paid to all road users: pedestrians, (especially children), bus drivers and passengers, cyclists as well as motorists, especially for urban schemes, and their needs should be considered. In order to achieve this, the auditors should take the role of all users and try to predict/visualise, as precisely as possible, the way different users will perceive the scheme (‘drive, ride, walk’ concept).

- Consultation with experts outside the auditing team (such as traffic signals engineers, the Police) may be necessary.

Manuals

Every country uses manuals of their own, nevertheless all designers of manuals have looked at the UK manual. Except for the UK Department of Transport regulations and the TNZ procedures conducted on a 20% sample on state high ways, they are *guidelines* and do not have to be obeyed unquestionably.

| Manuals used | | |
|----------------|-----------------------------|---|
| United Kingdom | Dept.of Transport | Compulsory RSAs |
| | I.H.T. | Guidelines for the Safety of Highways |
| | Various Counties | Various manuals |
| Denmark | Road Directorate | Manual of Road Safety Audit |
| Norway | Public Roads Administration | Guidelines for inspection and Quality Audit |
| Australia | Austrroads | Principles and advice on good practice |
| New Zealand | Transit New Zealand | Guidelines to policy and procedures |

Utilization

When conducting a RSA, the audit team should not try to redesign the scheme, instead they should pay attention to road safety for all kinds of different road users, and their suspected road user behaviour. The way this should *not* be done, is to compare the design with relevant standards and see if it matches, but the audit team should check if the design appropriately interacts with the design standards, for strictly applying standards does not always lead to a safe road.

Some other findings about RSA are mentioned below. It is important that a site visit is carried out. Both in daylight and at night. Thus the visibility for different road users can be checked in the context of the road and its surroundings. When a RSA is carried out in an early stage of the design process it is less likely that ‘errors’ become embedded in the design and become harder to correct later on. A RSA should not seriously delay a design process, thus attention should be paid to the embedding of the RSA during the planning of the design process. Attention should be paid to monitoring and feed back to the audit team after opening of the road when accidents occur.

The RSA process should be formally organised and its outcomes documented. Concerning the formalization and purity of an audit, it is to be recommended that the audit results are documented before there is discussion (if any) with the client, and concessions could arise. Some say that a formalised RSA leads towards a more systematical approach and enlarges the chance of a consistent outcome. The ultimate grade of formalisation is to make a RSA mandatory. Relevant plans and documents should be available to the audit team and should be mentioned in the audit report. It should be clear what should be audited, which tasks there are, and who is responsible for those tasks. It can be beneficial to use the same names and numbers of stages for less misunderstandings and for a better comparison with other RSA documents.

Time spent by auditors

The time spent on conducting a RSA varies considerably. The responding consultants in a British survey needed 8 to 109.3 hours with an average of 58 hours to complete a RSA. The RSA undertaken by the local authorities themselves took from 2 to 80 hours, with an average of 21 hours. The overall weighted average for completing an audit was found to be 25 hours. Time could be reduced in the later stages if a feasibility stage RSA was carried out and there were informal consultations throughout the design of the scheme.

Redesign Costs

The following table indicates the average percentage of construction cost as a result of redesign due to the audit, compared to the original construction cost for varying sizes of schemes. The combined average percentage for audits carried out by both local authorities and consultants, was found to be 0.72 %. Smaller schemes tend to require a greater percentage. In some cases the audit team recommendations even led to a cost reduction.

| <i>Road Safety Audit costs in the United Kingdom</i> | | | | |
|--|-------------------|-----------------|-------------|----------|
| Size of scheme | Local Authorities | | Consultants | |
| | Percentage | Range | Percentage | Range |
| < £ 500,000 | 3.36 % | -3.1 % - 33.3 % | 1.6 % | 0 - 10 % |
| > £ 500,000 | 0.24 % | 0 % - 10 % | 1.16 % | 0 - 5 % |
| All schemes | 0.35 % | -3.1 % - 33.3 % | 1.16 % | 0 - 10 % |

Source: Crafer (1995)

Proposal for the development of a framework

A framework for the development of RSAs can be found in five points containing tasks for the different bodies responsible for different aspects of road safety.

- National governments should develop RSA procedures and methods.
- National road authorities should perform pilot audits for all roads, including TERN.
- National organisations responsible for design guidelines & manuals should integrate RSA in tools for improving road safety.
- National road research institutes should evaluate RSA.
- European Commission should initiate pilot audits on TERN roads. These pilots should point out how the audits for TERN roads will be performed, with regard to all previously recognized ‘levels’; procedures, the audit team, and responsibilities.

Introducing RSA

Probably the best way of introducing RSA is ‘top-down’ (management and governmental) approval and ‘bottom-up’ (road designers) training. In this introduction stage the use of checklists could be useful. When introducing RSA, knowledge of accident investigation techniques or safety engineering is necessary. Another crucial point in introducing RSA is to how to tell when a designer is wrong. The best answer to this problem is probably an increase in accidents. On a European level, the procedure could perhaps be used in a highly aggregate level, using local knowledge of road safety when performing a RSA.

General conclusions

- Some European countries have developed a national RSA system. Many people involved in this development think of RSA as a promising way to improve road safety.
- RSA Pilot projects point out that design inaccuracies can be discovered in new road designs and RSA evaluations already carried out in some counties have been very positive; RSA seems to work.
- The introduction of a RSA system can either be done bottom-up or top-down. A bottom up approach can lead to a vast, enthusiastic participation, whereas a top-down approach can lead to a more explicit introduction.
- Although road safety comprising design solutions can be tracked using a RSA, the precise effects are yet still unknown.
- Quality is added to a national road system by using a RSA system.

1.3 The phenomenon Express road

Workpackage 3 dealt with express roads, in the Technical Annex of the SAFESTAR project provisionally defined as “[...] roads which are between the well known and well defined motorways on the one hand and ordinary single carriageway rural roads on the other.” An inventory in a number of EU countries showed that this type of ‘intermediate roads’ exist in most countries, although generally named differently. Express-type roads are often found in more than one category of the national road classification systems. In order to allow work to progress, more clarity was needed on what exactly an express road is. On the functional characteristics of express roads there appeared to be a high level of agreement in Europe. Based on the outcomes of an expert workshop on the issue and based on the inventory the following functional definition emerged (Van Schagen & Hummel, 1998):

An express road is a high capacity road for long distance traffic with limited access and closed for non-motorised traffic.

The last part of the definition (‘closed for non-motorised traffic’) means that express roads do not exist in the UK and Ireland, since in these countries all non-motorway roads are all-purpose roads, i.e. open to all traffic. In Sweden and Portugal a limited number of roads which would otherwise fall within the category of express roads, cannot be classified as such, because they are also open to non-motorised traffic.

The design characteristics of express roads differ widely both between countries and within countries in particular with respect to cross-sectional design (single and dual carriageway designs) and intersection design (at-grade or grade-separated). Therefore, it was impossible to come to a geometric definition.

From a detailed accident analysis on the Portuguese situation and from available data of other countries (Cardoso & Costa, 1998), it becomes clear that express roads have a bad safety record when compared to roads with a full motorway design. Compared to ordinary roads the situation is more complex. Whereas in terms of (injury?) accident rates express roads perform better than ordinary roads, the death rates are very similar, indicating that accidents on express roads generally result in more severe injury. Table 1.1 provides the data for the Portuguese road network.

Like on motorways, run-off-the-road accidents are the most frequent accident type on express roads. On ordinary roads lateral accidents are the most frequent accident type. Lateral accidents are the second most common accident type on single carriageway express roads, rear-end accidents on dual carriageway express roads and motorways. Table 1.2 presents the data on accident types as found in the Portuguese accident study by Cardoso and Costa (1998).

| | FATALITIES | | DEATH RATES (per 10 ⁶ Vehicle km) | | ACCIDENTS | | ACCIDENT RATES (per 10 ⁶ Vehicle km) | |
|--------------------|------------|------|---|-------|-----------|-------|--|-------|
| | 1990 | 1995 | 1990 | 1995 | 1990 | 1995 | 1990 | 1995 |
| All roads | 1298 | 1205 | 0.068 | 0.043 | 14478 | 15940 | 0.761 | 0.569 |
| 2x2 Motorways | 44 | 76 | 0.016 | 0.013 | 579 | 1121 | 0.215 | 0.188 |
| 2x2 Express roads | 14 | 33 | 0.022 | 0.029 | 261 | 503 | 0.415 | 0.448 |
| 2x2 Ordinary roads | 11 | 9 | 0.026 | 0.019 | 89 | 278 | 0.207 | 0.583 |
| 2x1 Express roads | 146 | 122 | 0.078 | 0.045 | 902 | 1020 | 0.48 | 0.373 |
| 2x1 Ordinary roads | 1083 | 965 | 0.081 | 0.054 | 12647 | 13018 | 0.944 | 0.734 |

Table 1.1 *Numbers and rates of fatalities and injury accidents on different types of roads in Portugal in 1990 and 1995.*

It is clear that for safety reasons it would be better not to build new express roads and to upgrade all existing ones to motorways. However, the decision on the type of road appears to be based mainly on (expected) traffic volume and financial resources. Occasionally, environmental and land use considerations play a role as well. Safety arguments, on the other hand, do not seem to play an important role in the decision making process. Although it seems justified to state that the vast majority of decision makers are well aware of the fact that from a safety point of view express roads are not a satisfactory option, other arguments seem to outweigh the safety arguments.

| | COLLISION | | | | HIT PEDESTRIANS | RUN-OFF- -THE-ROAD | SUM |
|-------------------|-----------|----------|---------|----------|--------------------|-----------------------|-----|
| | Frontal | Rear End | Lateral | Obstacle | | | |
| 2x2 Motorway | 2 | 25 | 8 | 5 | 4 | 47 | 91 |
| 2x2 Express road | 7 | 25 | 14 | 5 | 8 | 30 | 89 |
| 2x2 Ordinary road | 5 | 15 | 24 | 14 | 23 | 16 | 97 |
| 2x1 Express road | 16 | 16 | 25 | 4 | 8 | 29 | 88 |
| 2x1 Ordinary road | 20 | 11 | 29 | 4 | 11 | 20 | 94 |

Table 1.2 *Distribution of the (injury?) accidents in different road classes by accident type (percentages).*

Even if safety arguments would get a higher priority in the decision making process, e.g by applying strictly the one million ECU rule (saving one life justifies the investment of one million

ECU), there will still be situations where a motorway is not a realistic option, for example if the (expected) traffic volumes are low. If express roads are the only realistic solution, it must be made sure that their design is as safe as possible. In the next sections the recommendations for horizontal alignment, cross-section, safety devices (including road side safety) and intersections at express roads are discussed. Since experimental research on express roads is virtually non-existent, the majority of recommendations are mainly based on two-lane rural highways and interurban roads.

2. ALIGNMENT

2.1 Horizontal (and vertical) alignment

2.1.1 Express roads

From a safety point of view, curves are a critical design element in the horizontal alignment: According to Zegeer et al. (1992) accident rates are 1.5 to 4 times higher in curves than on tangents.

In Portugal, around 20 per cent of the accidents on dual carriageway roads (all categories) and 25 per cent of the accidents on single carriageway roads (all categories) happen in curves. The narrower the curve, the higher the accident rate (Hughes et al., 1997). Accident rates are particularly high in isolated curves, in the first of a series of curves or in narrow curve following a number of relatively wide curves (OECD, in preparation). Hence, for safety, the location and design of curves is of importance as well as the design consistency between curves.

The fact that accident rates in curves are higher than on tangent sections does not mean that curves should be avoided altogether. The use of straight sections longer than 5 km. is generally discouraged because of the risk of drivers becoming drowsy and less alert. In general, it can be stated that the design speed should be guaranteed throughout the entire road, including at curves. The following formula for determining safe and comfortable curve radii is recommended (Hummel, 1998):

$$R_h \geq \frac{V_0^2}{127(f_z + i/100)}$$

R_h = curve radius in m.

V_0 = design speed in km/h

f_z = side friction coefficient

i = superelevation in %

For determining the minimum radius for a given design speed, the side friction coefficient f_z is given in the following table. The friction coefficients f_z in this table are based on driving-comfort.

| | V_0 in km/h | | | |
|-------|---------------|------|------|-----|
| | 50 | 70 | 90 | 120 |
| f_z | 0.18 | 0.16 | 0.13 | 0.1 |

Most studies find a positive safety effect of transition curves, although some studies (e.g. O’Cinneide, 1995) report negative effects, possibly because drivers underestimate the subsequent curves. Hummel (1998) concludes that the use of transition curves on high speed rural roads (express roads) must be recommended for safety reasons. Superelevation also has a positive effect on safety, though it should not exceed 8%.

With respect to vertical alignment it can be concluded that safety is adversely affected when gradients increase: a slight increase in accident rates with gradients up to 6 or 7 per cent and a large increase beyond those percentages (Slop et al., 1996). The accident rates for downgrades is much higher than for upgrades (Zegeer et al., 1992; Slop et al., 1996). When the horizontal alignment is relatively bendy, the negative effect of steep gradient increases.

A specific effect of vertical alignment is the blind effect caused by vertical convex curves, affecting the sight distance. This seems to be of particular importance for single carriageway express roads. Slop et al. (1996) present the following formula for determining the radius of a convex vertical curve:

$$R_v = \frac{0,5 S_a^2}{(\sqrt{h_e} + \sqrt{h_o})^2}$$

R_v = radius of vertical curve (convex)

S_a = actual sight distance

h_e = eye height

h_o = object height

The value to be substituted for S_a depends on what the designer wishes to offer to the road user. The minimum requirement is the stopping sight distance.

Regarding concave (sag) curves a minimum radius of 3,000 m. is recommended in order to avoid insufficient sight distance when using dipped headlights at night.

2.1.2 Rural roads

This report uses design consistency or relation design as the leading design principle for the horizontal alignment. Successive straight and curved road sections should be related to each other in such a way that road users will not be subjected to unexpected and uncontrollable changes in the horizontal alignment.

The procedure for attaining a consistent design is based on both qualitative models which relate design elements to the operating speed (V_{85}), and a comparison between the calculated operating speed and the design speed.

Tangents and curves

Both design consistency and relation design are an important part of the design philosophy in this report. However, it is a fairly theoretical principle from the (accident) researchers' point of view. The relationship between consistency characteristics and road safety indicators is still the subject of research.

One of the assumptions in this respect is the influence of the length of a tangent on the speed in the curve. Lamm et al. (1988) considered this as an essential element in their methodology for relation design. But Fink & Krammes (1995) showed that this influence is rather small or non-existent regarding the relationship between accident rate, degree of curve and length of tangent. The influence of the preceding tangent is mainly concentrated in the speed at the end of the tangent and the speed reduction when entering the curve. Cardoso (1996) related these two types of speed to the accident rate in both curve and tangent (lane width and AADT are also part of this relationship).

Instead of using speed indicators, one can use a less direct indicator for the safety of the road. This indicator is the work load of a (car) driver. It is supposed to be related to the complexity of the road and traffic environment. Messer et al. (1981) have developed a methodology for determining the work load of a driver on a given road. The work load is determined by scoring the level of complexity of different road and traffic elements of a given road section, of the preceding, and of the following road sections.

However, this methodology proved to be very dependent on expert opinions.

Krammes et al. (1995) have introduced an alternative method: the vision occlusion method. In this method drivers are asked to drive with their eyes closed until they think it is necessary to open them again. The time period they drive with their eyes open is considered to be an indicator for the work load. The work load is:

- $WL = 0.193 + 0.016 \cdot D$ for curves, D is 'degree of curve' and $R^2 = 0.90$;
- $WL = 0.176$ for tangents.

The value for tangents implies that drivers drive with their eyes open in only 17,6% of the time they are driving on tangents.

Operating speed

In general operating speed and road class are highly correlated, e.g. main roads have been designed in such a way that high speeds are possible and acceptable. However, many local circumstances will temporarily or permanently influence the operating speeds, like bendiness, density of traffic, crossing traffic, atmospheric conditions, road width etc. Road design deals mainly with conditions which are permanently present and which are more or less ideal: vehicles are in a free flow, only influenced by infrastructural elements. These type of conditions have been related to operating speed by means of statistical relationships (models): The operating speed on a cross-section (spot) is related to the characteristics of that cross-section and of the road section. This spot speed approach (one cross-section) seems, besides the original question, to find a relationship between horizontal alignment and the speed along the road section (speed profile). Spot speed is not quite the same as the speed profile (horizontally varying) of a road section. But a speed profile can be 'constructed' by choosing the spots at important road features which make the speed change substantially. The most dominating feature in this respect is a curve. Many relationships between operating speed and curve characteristics have been developed; Cardoso et al. (1997) have given an overview. Some of these relationships are given below in order to show the type of relationships:

Lamm & Choueiri (1987) derive V_{85} from the relationship:

$$V_{85} = 34.700 - 1.005 DC + 2.081 LW + 0.174 SW + 0.0004 AADT \quad (1)$$

$R^2=0.842$

V_{85} : 85-percentile speed in mph

DC: 'degree of curve' (0° tot 27°)¹
 LW: lane width in ft.
 SW: shoulder width in ft.
 AADT: annual average daily traffic (400 to 5000 motorvehicles per day)

A more simple relationship is given by the same authors:

$$V_{85} = 58.656 - 1.135 DC \quad (2)$$

$R^2=0.787$

This more simple model (2) is also available for lane widths of 10, 11 and 12 ft.

Collins & Krammes (1996) have found the following relationship:

$$V_{85} = 102.4 - 1.57 DC + 0.012 L - 0.10 \Delta \quad (3)$$

$R^2=0.82$

V_{85} : 85-percentile speed in km/h
 DC: 'degree of curve'
 L: curve length
 Δ : 'deflection angle' ($=L*D/100$)

Results from SAFESTAR

The relationship between operating speed V_{85} and road characteristics was modelled for both curves and tangents. The following characteristics of the curves were available:

- curve radius (in m)
- curve length (in m)
- lane width (in m)
- shoulder width (in m)
- longitudinal gradient (in m per 100m)

Speed models for curves were fitted using data from Greece, Finland, France, and Portugal. The number of available curves was 5 from Finland, 30 from France, 9 from Greece, and 36 from Portugal. Speed measurements added up to 10,000 vehicle speeds in each country.

Separate models were fitted for each country. A general model, using the data of the four countries, was also fitted. However this general model still needs a (constant) factor for explaining a part of the 'national' statistical variance. Worse is that this general model is not statistically significant regarding this constant factor. A general model which was independent from the national differences could not be fitted. So only the four separate models remain to be used. These for national models for curves are:

¹⁾ The relationship between the radius of a curve (R) and the degree of curve (DC) is: $R=5730/DC$ (R in feet) or $R=1746.4/DC$ (R in m).

$$\text{Finland: } V_{85} = 51.756 - 337.780 / \sqrt{R} + 0.6049 * V_{85, AT} \quad (4)$$

$$R^2 = 0.707$$

$$\text{France: } V_{85} = 49.220 - 292.736 / R^2 + 0.454 * V_{85, AT} \quad (5)$$

$$R^2 = 0.801$$

$$\text{Greece: } V_{85} = 41.363 - 294.000 / \sqrt{R} + 0.699 * V_{85, AT} \quad (6)$$

$$R^2 = 0.916$$

$$\text{Portugal: } V_{85} = 25.010 - 271.500 / \sqrt{R} + 0.877 * V_{85, AT} \quad (7)$$

$$R^2 = 0.896$$

V_{85} : 85 percentile speed (in km/h)

R : curve radius (in m)

$V_{85,AT}$: 85 percentile of the unimpeded speed on the tangent preceding the curve (in km/h)

Figure 2.1 shows these relationship graphically for an approach speed of 90 km/h. The differences between the four countries are rather small, except for the curve speeds at small radii in France.

Tangents

Speed models for tangents were also fitted separately for each country, because a general model could not be fitted. Many different characteristics of the tangents were used in fitting the equations:

- average bendiness (total deflection angle along the tangent; in degrees per m)
- average lane width (in m)
- average shoulder width (in m)
- total percentage upgrade
- total percentage downgrade
- average gradient (in m/km)
- total hilliness (sum of elevation change, both upgrade and downgrade; in m/km)

The number of available tangents was equal to the number of curves: 5 from Finland, 30 from France, 9 from Greece, and 36 from Portugal.

The selected characteristics are the outcome of a statistical optimization process. The literature review did not reveal theoretical models which give a sound basis for a 'true' relationship between tangent speed and road characteristics. National differences concerning topography, land use, road design, and road user behaviour appear to be an important factor for the

resulting set of road characteristics. So, for each country, a different set of road characteristics was found to be related to tangent speed.

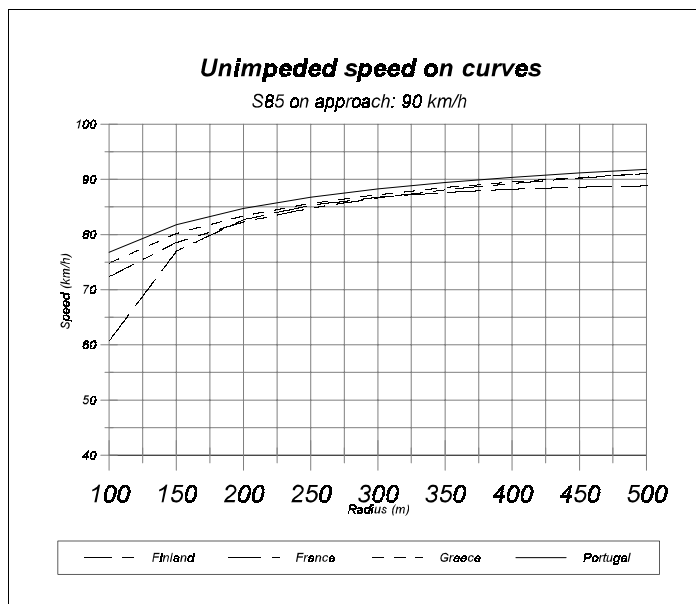


Figure 2.1 *Unimpeded speed at a curve related to curve radius, using data from four different countries*

$$\text{Finland: } V_{85} = -17.17 + 0.02657 * L + 33.711 * LW - 21.936 * SW \quad (8)$$

$$R^2 = 0.768$$

$$\text{France: } V_{85} = 97.737 + 0.007436 * L - 45.707 * Bend \quad (9)$$

$$R^2 = 0.653$$

$$\text{Greece: } V_{85} = 134.069 - 3.799 * Hill - 126.59 * Bend \quad (10)$$

$$R^2 = 0.918$$

$$\text{Portugal: } V_{85} = -29.95 + 34.835 * LW + 0.0347 * Prad - 43.124 * Bend \quad (11)$$

$$R^2 = 0.821$$

V85: 85 percentile of the unimpeded speed (in km/h)

L: tangent length (in m)

Bend: bendiness (in degree/km)

LW: lane width (in m)

Hill: hilliness (in %)

Prad: curve radius of the curve preceding the tangent section (in m)

Results from SAFESTAR

Accident rate models were fitted for both types of input: speed indicators and work load. The road characteristics which were used for these models were:

- average daily traffic (all motorized vehicles in both directions)
- maximum estimated spot speed on each road element (both directions)
- maximum estimated approach speed on each curve element (both directions)
- maximum estimated speed reduction from preceding element (both directions)
- sum of estimated speed reductions form preceding element (both directions)
- curve radius
- length
- length of preceding tangent (in case of a curve)
- shoulder width
- grade (longitudinal gradient) of a curve

The database consisted of 1,000 road elements, with a total length of 611.7 km, in three countries, Finland, France, and Portugal. However, the number of accidents on the Finnish roads appeared to be too low for fitting equations to data (many elements with no accidents at all). So it was decided to fit the models with the data from France and Portugal (269.5 km road length).

The curve models have been fitted for France and Portugal separately:

$$\text{France: } AR = \frac{e^{21.98} * AADT^{0.5745} * MaxRedV_{85}^{0.3518}}{MaxV_{85}^{0.5,017}} \quad (12)$$

$$R^2 = 0.58$$

$$\text{France: } AR = \frac{AADT^{0.2536} * WL^{5.536} * MaxAppV_{85}^{3.031}}{e^{4.708} * LW^{2.355}} \quad (13)$$

$$R^2 = 0.54$$

$$\text{Portugal: } AR = \frac{AADT^{0.4174} * MaxRedV_{85}^{0.008172}}{e^{0.4284}} \quad (14)$$

$$R^2 = 0.20$$

$$\text{Portugal: } AR = \frac{AADT^{0.4065} * WL^{0.6420} * MaxAppV_{85}^{0.6370}}{e^{2.582}} \quad (15)$$

$$R^2 = 0.24$$

AR: accident rate (number of accidents per million vehicle miles)
 AADT: (average daily traffic)
 MaxRedV₈₅: maximum estimated speed reduction from preceding element (both directions)
 MaxAppV₈₅: maximum estimated approach speed on each curve element (both directions)
 MaxV₈₅: maximum estimated spot speed on each road element (both directions)
 WL: work load (Krammes et al., 1995)

Obviously, the French models fit better than the Portuguese models. The databases of both countries were merged in order to fit more general curve models. This resulted in models with rather low R² values:

$$AR = \frac{AADT^{0.4057} * MaxRedV_{85}^{0.09947} * MaxAppV_{85}^{0.6556}}{e^{1.839} * LW^{1.14}} \quad (16)$$

R² = 0.13

$$AR = \frac{AADT^{0.316} * WL^{1.593} * MaxAppV_{85}^{2.433}}{e^{6.957} * LW^{2.034}} \quad (17)$$

R² = 0.18

The accident rate on curves according to equation (16) has been put into a graphical representation (Figure 2.2). The accident rate in Figure 2.2 was calculated with an approach speed of 100 km/h and an AADT of 7,000 motor vehicles per day.

The modelling for tangent elements resulted in two national models:

$$France: \quad AR = \frac{e^{13.72} * AADT^{0.1638}}{MaxV_{85}^{2.881} * LW^{0.2528}} \quad (18)$$

R² = 0.09

$$Portugal: \quad AR = \frac{e^{0.9453} * AADT^{0.5246}}{MaxV_{85}^{0.06281} * LW^{0.7000}} \quad (19)$$

R² = 0.33

AR: accident rate (number of accidents per million vehicle miles)
 AADT: (average daily traffic)
 MaxV₈₅: maximum estimated spot speed on each road element (both directions)
 LW: lane width (in m)

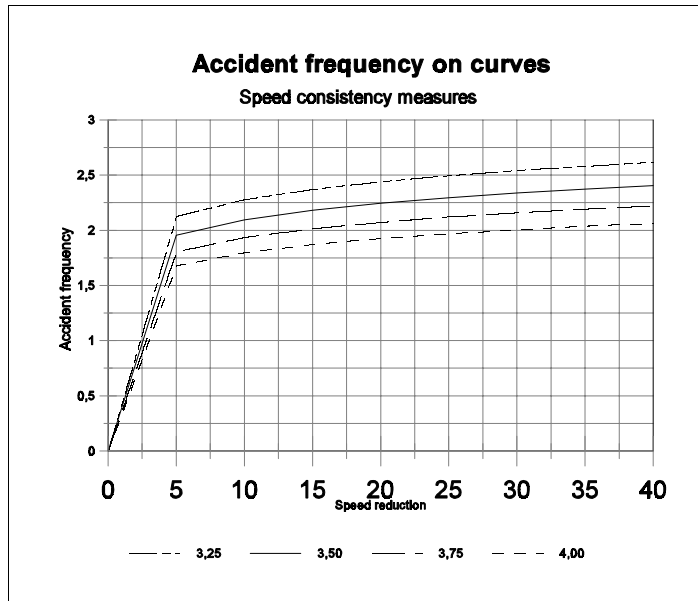


Figure 2.2 *The relationship between accident rate (AR) and speed reduction ($MaxRedV_{85}$) for different lane widths (LW)*

2.2 Marking and Signing in Curves

The effects of different signing and marking principles have been studied by the Danish Road Directorate, in cooperation with SETRA-CSTR and CETE Normandie Centre in France. The Dutch institute TNO has also contributed with a simulation test.

In this workpackage, a framework is developed to classify substandard horizontal curves on rural roads into a number of danger categories. A basic signing and marking concept, which should be the minimum applied to curves belonging to the relevant category, is associated with each of the danger categories.

By the use of both simulation and full scale tests, the effectiveness of the proposed signing and marking strategies is tested.

2.2.1 Current practice

Since the early days of motorised traffic, signs have been used to warn drivers that they are approaching a substandard curve. To establish a safe and comfortable journey through substandard curves, advisory speed signs, curve warning signs, background markings, and markings on the road give an indication of the desirable speed.

Current practice for the use of signing and marking of substandard curves differs widely. Even within individual EU-member states, there proved to be considerable variations in actual signing and marking of identical substandard curves. There seem to be no clear relation between the actual 'danger category' of a substandard curve and the applied signing and marking of that curve. Because road-users do not receive consistent information on the approach of a substandard curve, the choice of correct speed and driving behaviour is often difficult.

Safe and efficient traffic behaviour is greatly influenced by the geometrical features of the road. A review of accident-spot maps show that accidents in rural areas tend to cluster on curves, particularly on very sharp curves. In Denmark, 20% of all personal injury accidents occur on rural road curves, and 13% of all fatalities in traffic accidents occur at horizontal curves in rural areas. The situation in France is even worse. Here 21% of all fatalities occur in curves on rural roads. A similar situation prevails in the rest of Europe.

Curve accidents are mainly caused by improper (too high) speeds. Many of those speed errors can be related to inconsistencies in the horizontal alignment which surprises drivers by sudden changes in road characteristics. As a result they exceed the critical speed of a curve, leading to loss of control over their vehicle.

It can be very difficult for road users to perceive horizontal curves, and it is almost impossible to estimate the design speed before entering the curve. Serious safety problems occur in situations where large differences exist between the operating speed on the upstream horizontal alignment (the approach speed) and the design speed of the substandard curve. Two main approaches can be distinguished for solving this problem:

- make the design speed of the curve similar to the approach speed;
- use marking and signing of curves to provide the driver with the information needed for correct and timely estimation of the design speed.

For financial reasons the former approach is often not possible. In most cases signing and marking is therefore the only remaining approach for solving safety problems on curves.

2.2.2 Conceptual approach

In order to establish a more uniform use of signing and marking and thereby increasing road safety, a framework for signing and marking of substandard curves is developed. The purpose of the framework is to create a tool for road authorities to classify curves on rural roads into a number of danger categories in a structural and uniform way. When a unique and uniform signing and marking strategy is used for each danger category, the choice of correct speed and driving behaviour is simplified, resulting in an increase in safety on curves.

The input parameters of this approach are the approach speed on the horizontal alignment and the design speed of the curve. When the input values are known, the danger category of the road curve is determined by a model. The determined danger category of the curve automatically results in a recommended signing and marking strategy for that curve.

Approach speed:

The final signing and marking plan on each curve should be based on real speed measurements. For any overall classification of a large number of curves, the following formula for estimating the approach speed on two-lane rural roads has been developed:

$$V_a = \sqrt{0.07716 * V_{2n-1}^2 + 2 * 0.8 * (L - 100)}$$

V_a : approach speed (km/h.)

V_{n-1} : 85th percentile speed of the previous curve (m/s)

L: distance between the present curve and the previous curve (m)

Depending on the type of road V_{n-1} is calculated with one of the following formulas:

2-lane and 3-lane roads with minimum width of 6 m.: $V_{n-1} = 102/(1 + 346/R^{1.5})$
 2-lane roads with a width less than 6 m.: $V_{n-1} = 92/(1 + 346/R^{1.5})$

Design speed of curve

The design speed of a curve is the speed at which a passenger car can drive, in a safe, controlled, and reasonably comfortable manner, through a curve under normal weather and road conditions when the road surface is wet.

Estimation of the design speed is done with the aid of models or formulas. A simple but internationally used and accepted formula for estimating curve design speed is the fundamental curve-design equation:

$$V_d = \sqrt{R * g * (e + F)}$$

- V_d : curve design speed (m/s)
- R : radius of curve (m)
- g : acceleration due to gravity (9.81 m/s²)
- f : side friction factor
- e : superelevation

The side friction factor depends on the condition of the road surface, the tyres of the vehicle and the vehicle speed. Most national guidelines for road construction table include average values for the side friction factor. The following table shows average values for the side friction factor as used in Denmark.

| | Design speed in km/h | | | | | | |
|---------------------------|----------------------|------|------|------|------|------|------|
| | 60 | 70 | 80 | 90 | 100 | 110 | 120 |
| Side friction factor (DK) | 0.18 | 0.16 | 0.14 | 0.12 | 0.10 | 0.08 | 0.07 |

Classification of substandard horizontal curves

When the approach speed on the horizontal alignment and the design speed of the curve are known, the developed model can be used to determine whether a curve is to be classified as ‘substandard’. In the case a curve is substandard, the danger category in which the curve can be classified, can be determined with the same model.

The model is calibrated for the Danish road network. The authors stress that the model can only be used outside Denmark after calibration for the prevailing national conditions.

Curves with a design speed higher than, or equal to the approach speed are not regarded as substandard curves. Signing and marking is therefore not required on these curves.

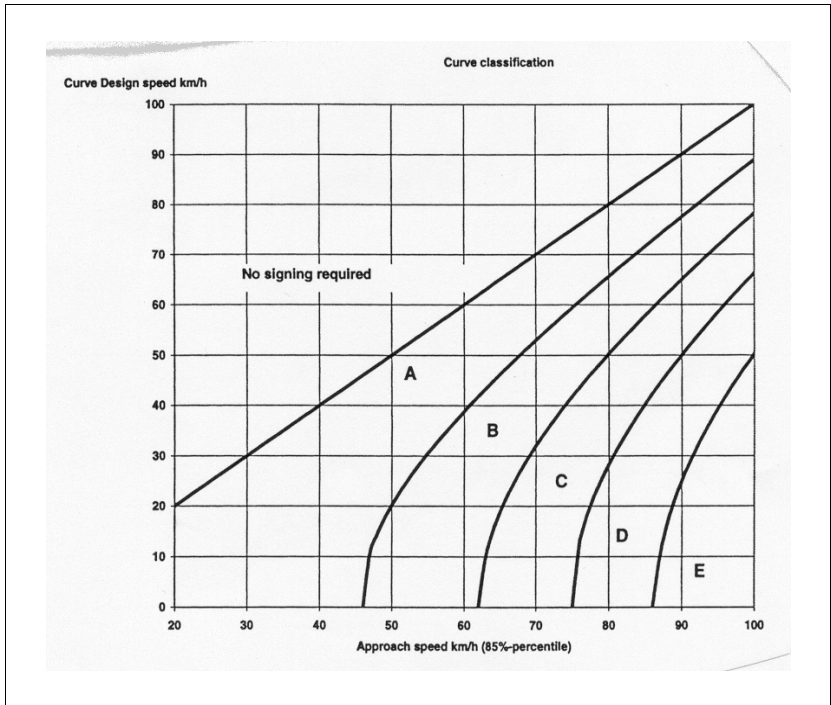


Figure 2.3 Model for classifying horizontal substandard curves into danger categories

Basic signing and marking

Based on existing literature, several national signing and marking guidelines in Europe, expert-meetings, a simulator test and full-scale tests in Denmark and France, the following concepts for signing and marking of curves have been developed.

Each basic signing and marking concept consists of one or more of the five elements:

- delineators
- centre line and edge lines
- advance warning
- advisory speed signs
- chevron signs.

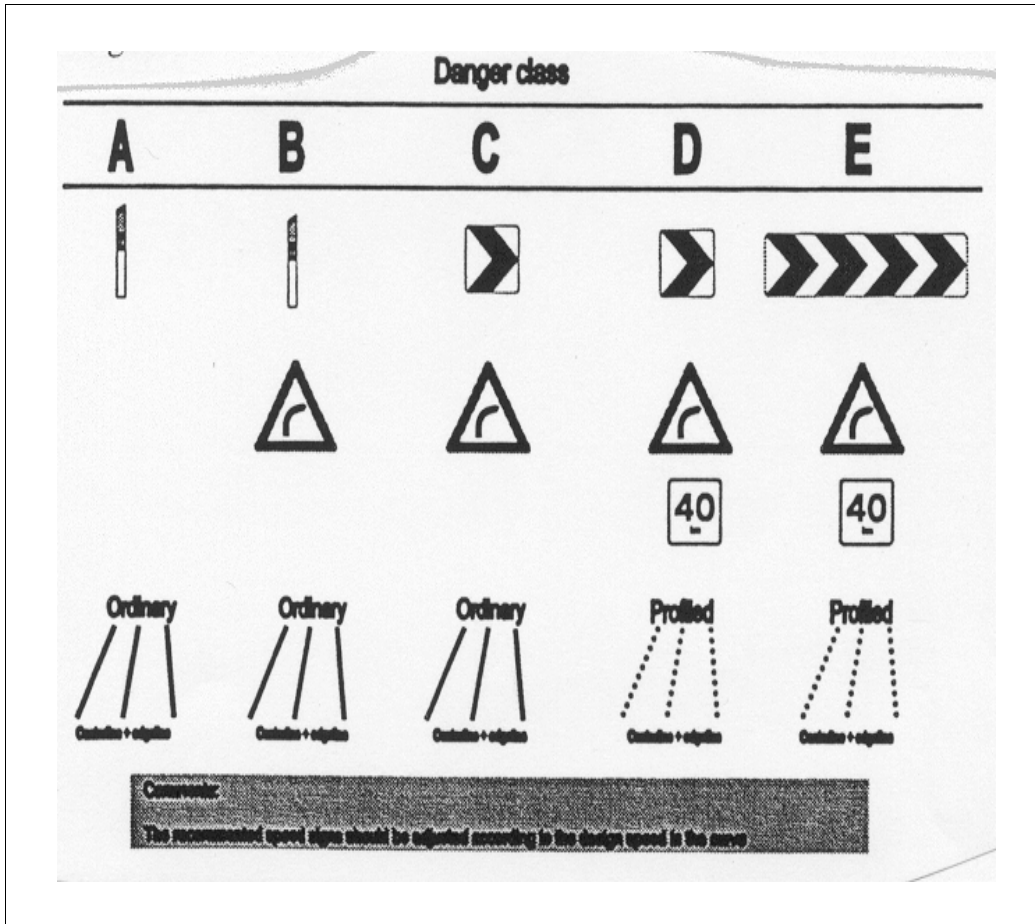


Figure 2.4 Basic signing and marking for each danger category

2.2.3 Evaluation of new types of marking

Centre and edge lines should be used at all substandard curves. On curves in the danger categories A, B, and C, the lines can either be ordinary painted/thermoplastic lines or profiled lines. Based on research in Denmark and other countries, profiled edge and centre lines are recommended for curves belonging to danger category D or E.

In this study, the effects of profiled road markings were studied on four test curves in Denmark. On the test curves 'vibracomb' lines were used as edge and centre markings. These vibracomb lines consist of an ordinary line to which a profiled line is attached, like the teeth of a comb. The teeth of the comb are pointing towards the vehicle lanes.

Visibility of these profiled markings proved good, because of their height. Moreover, an audible rumbling effect occurs when a rotating tyre touches them, thus giving the driver an audible rumbling warning.

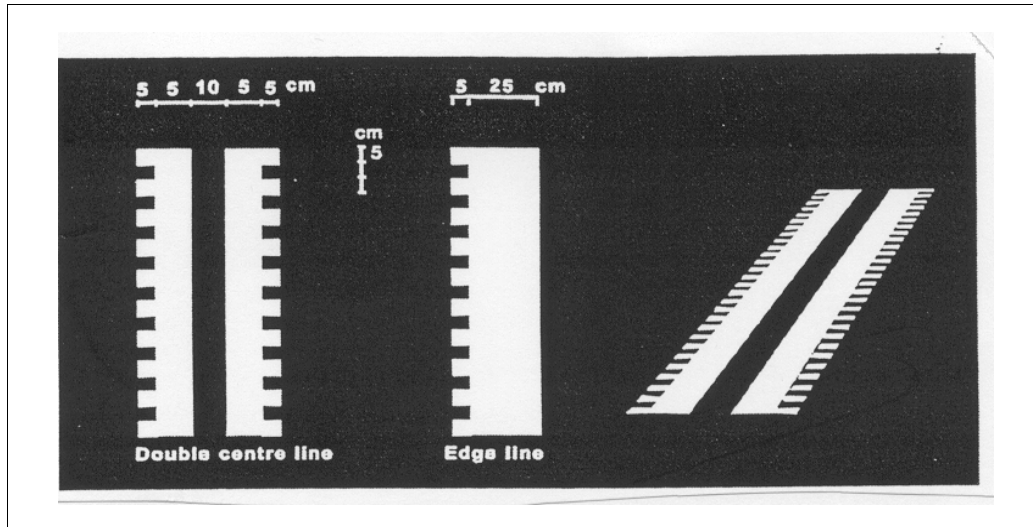


Figure 2.5 *Vibracomb line*

Although tendencies towards speed reduction were observed on the curves with vibracomb lines, the observed changes were not significant.

The number of vehicles infringing the centre line proved to decrease on the curves with vibracomb centre lines.

These positive effects are supported by other research studies on profiled markings in Europe and the USA. Here profiled lines also improved driving behaviour and reduced infringements of both centre lines and edge lines. Accident studies showed a reduction of the number of run-off accidents by 60% - 70% on curves with profiled edge lines.

Tests with road studs, as conducted in this study, showed less positive results. The test showed that the costs of applying the road studs were high, and that their retro-reflective capacity was reduced to almost zero within a few days, because the self-cleaning function did not operate as expected. Furthermore, most of the road studs were destroyed after only one or two months, due to winter maintenance.

2.2.4 Recommendations for road design

Simulator tests and full scale tests proved the positive effects of the developed signing and marking strategies for the different danger categories. Additional positive effects due to the more uniform signing and marking strategies and the improvement on the recognition of dangerous curves, add to the value of the developed signing and marking strategy.

The use of this structural approach should therefore be recommended.

Detailed recommendations on when and how to apply signs and markings are given by Nielsen et al. (1998).

The study on signing and marking on curves in rural roads also gives a number of measures that can be added to the basic signing and marking of curves where special road safety problems occur.

Poor visibility of the curve

- Vegetation: Vegetation on the inner side of a curve makes the curve less visible and should be reduced. Vegetation, such as shrubs and small trees on the outer side of the curve, will on the other hand improve the visibility of the curve and also give good guidance through the curve. This is especially valid during daylight.
- Pavement marking: In some cases painted signs on the road surface can improve the alertness of drivers.

Poor readability of curve

- Vegetation: Vegetation on the inner side of a curve makes the curve less visible and should be reduced. Vegetation, such as shrubs and small trees on the outer side of the curve, improves perception of the direction and the sharpness of the curve in daylight.

High speeds

- Perceptual illusions: Special road markings may help the driver to choose the most adequate speed at places where the accident risk is often underestimated.
- Electronic speed sign: Electronic advisory speed signs which show the curve design speed, and flash when a vehicle exceeds this speed, can help estimating the correct speed.
- Improved road surface: A rough road surface, which increases the noise level in the vehicle, or a surface in a different colour can also cause drivers to choose a lower speed.
- Pavement marking: In some cases painted signs on the road surface can improve attention.
- Humps: The use of speed humps in the approach can effectively reduce speeds in the curve.
- Carriageway width: Reduced carriageway width on the approach and on the curve itself can reduce speed.

High frequency of run-off-the-road accidents

- Hard shoulder: Improvement of the verge e.g. by making a paved hard shoulder, can reduce run-off-the-road accidents.
- Safety barriers: Safety barriers do not reduce the number of run-off-the-road accidents, but can reduce the severity of these accidents.
- Road surface: Improvement of the friction of the road surface can reduce the number of run-off-the-road accidents

High frequency of head-on collisions

- Ghost island: A central hatched island increases the distance between opposing vehicle and thus reduces the risk of head-on collisions. Double continuous lines can give comparable results.
- Hard shoulder: A possible cause for head-on collisions is the overcompensation after running off the road. These accident types can be reduced by the presence of a hard shoulder.

3 CROSS-SECTION

3.1 Motorways: specific safety measures for emergency lanes and shoulders

Accident statistics of several European countries indicate that a sizeable proportion of accidents on motorways is related to emergency lanes. The cause of these accidents seems to be inappropriate use of the emergency lane and the nearside lane, for instance: vehicles avoiding ruts in the road surface by partially driving on the emergency lane.

This study is aimed to provide an analysis of accidents that are related to the use of emergency lanes in different European countries and subsequently produce an accident typology. This typology will then be used to derive possible countermeasures to prevent these accidents. The nature of this task is an exploratory one. The results could be used as a starting point for discussion with road authorities in the TERN-framework.

The work has consisted of five steps:

1. A general literature review to compile existing standards and policies.
2. An analysis of relevant accidents, using as example the European databases
3. A behavioural study of road users, specifically with respect to the inappropriate use of emergency lanes. This study will primarily consist of a literature review, supplemented by field observations.
4. Summarizing and interpreting the results and producing recommendations for practical countermeasures. Attention will also be paid to the different conditions on bridges and in tunnels.

The target groups are supranational bodies and national authorities in the EU countries responsible for the safety of road infrastructures.

3.1.1 Literature review

At first a study of the literature was carried out. Additional standards and practices about emergency lanes were collected by means of sending questionnaires to all of the European countries, and correspondence and interviews with colleagues of European research institutes. By means of the questionnaires, accident data of the different countries was also requested. Owing to the poor response to this item, the main national road safety research centres were asked to deliver the data on multiple and single vehicle accidents on emergency lanes of motorways.

Survey of international standards and policies

The development of motorway standards is coordinated by the Motorway Working Group (MWG) of the Directorate General DGVII Transport. EFTA countries were invited to join the MWG, and further contacts with Central and Eastern European Countries (CEES) have been developed for making agreements.

The agreements about emergency lanes contain a few recommendations concerning the emergency lanes of motorways and a few operational regulations. These recommendations do not have a mandatory status.

In order to harmonize the National standards, the START-report 'Road Typology in the TERN' (1994) proposed a minimal number of conditions for emergency lanes of motorways. Summarized, the following international recommendations on motorways emergency lanes and hard shoulders have already been made:

- a minimal width of traffic lanes on straight alignment is recommended (3.5 m);
- a minimal width of hard shoulder (paved or stabilized) is recommended (3.75 m);
- the shoulders should normally include a continuous emergency stopping strip (of at least 3.00m);

In order to prevent improper use of emergency lanes and to reduce the number of stopped cars, the typical facilities spacing is recommended by Motorway Working Group (MWG) of the Directorate General, DGVII: rest areas with parking and toilets (every 20 km), service areas (every 50 to 100 km), and service and accommodation areas (every 200 km).

Also the presence of emergency calling posts are recommended:

- they are to be placed every two kilometres in each direction and opposite each other (in order to avoid the perceived possible need to cross the road);
- notices explaining their functions, fixed on emergency telephone boxes;
- make an European leaflet on motorway use to indicate the circumstances in which hard shoulders should, and should not, be used. Include instructions concerning emergency telephone use and explaining the functions of the telephones.

The relevant available national standards and practices in EU countries were collected and reported by Braimaister (1998). It deals with:

- Standards, guidelines concerning motorways design
- Main road design characteristics
- Traffic regulations on use of emergency lanes of motorways.

Design characteristics and regulations

Using the results of the questionnaires and the additional information by E-mail, the following design characteristics of emergency lanes and traffic regulations on use of emergency lanes of motorways were collected from the different European countries.

Main design characteristics

The width of emergency lanes is considered as most important design characteristic. Accordingly to the recent TERN-typology (START), the width of emergency lanes on TERN-motorways should be at least 3.00 m. The present norms in most of the EU countries do not meet this requirement. Only France (partly), the Netherlands, Portugal, and the UK have already standards which meet this requirement; or they have greater widths. In other countries, the width of emergency lanes is mostly 2.5 m.

Emergency phones

The presence of emergency phones on motorways is better harmonised. Almost all of the European countries have such phones every 2 kilometres on motorways (in UK even every 1.5 km). Finland and Sweden do not have emergency phones at all.

Traffic regulations

In all the EU countries, the traffic regulations commonly prohibit use of emergency lanes for regular traffic. The purpose of emergency lanes is to give space for emergency stops of vehicles and the use by special vehicles which belong to police, ambulance, or fire brigade.

There are discrepancies in the lists of reasons, which are to be accepted as emergency cases in different EU countries. All the countries respect the following reasons:

- police, fire brigade, or ambulance in action
- road maintenance in operation
- a breakdown of a vehicle
- driver suddenly becoming unwell.

All the countries, with exception of Germany and Greece, respect the reason for stopping on emergency lanes in case of 'actual shortage of fuel'. Such a 'reason' is to be considered as a violation of traffic rules.

'Assistance in case of an accident' is not allowed as reason to stop the vehicle on an emergency lane in UK and Sweden. Such a reason as 'being at police disposal as a witness' is legal in Belgium, Denmark, Finland, Luxembourg, Netherlands, and UK. But France, Germany, Greece, and Portugal do not accept such a reason. All the countries, with the exception of France, accept 'extremely bad weather conditions' as sufficient reason to stop the car.

Exceptional practices

There are also some less frequent exceptional practices in some countries:

- driving escorted by police;
- driving public bus on the specially marked hard shoulder during a traffic jam;
- as additional traffic lane when special traffic sign is open, due to high traffic volume.

Recommendations

Since the recent TERN-typology does not have such a list of reasons, a recommendation should be made to harmonise these lists in order to avoid dangerous situations caused by discrepancies in traffic regulations and usual behaviour in different countries.

3.1.2 Databases on road accidents and exposure

The international databases have been studied with the intension to estimate the accident risk on motorways and emergency lanes of motorways. For the risk calculation the following data should be available:

1. total numbers of accidents and casualties on motorways;
2. types of accidents, with at least one of the involved vehicles entering or leaving the emergency lane (hard shoulder) of motorways;
3. accident data for a number of years (at least for 3-4 years).

At least the following exposure data is necessary to be able to estimate properly the relevant accident risk:

4. total length of motorways;
5. percentage of motorway length with and without emergency lanes (hard shoulders);
6. AADT on motorways.

The main available databases were consulted in order to find available data for fifteen member countries of the EU. But not in any European database was there data available of multiple accidents on emergency lanes. One could expect in the near future that the relevant accident data will be available in the European database CARE.

To get the data sooner, the only possible way is by means of performing extra and expensive research. Within the limited budget of SAFESTAR it was not possible to realize this research in all countries. Owing to the missing data, only an estimation could be made of the volume and risk of multiple accidents on emergency lanes in European countries.

Only in two countries was data found from multiple injury accidents on emergency lanes and accident rates: United Kingdom (1979-1980) and the Netherlands (1979-1982; 1992-1995). To this data, exposure data from IRTAD database was added.

In order to estimate the risk of multiple accidents on emergency lanes on European countries, the available *total* accidents on motorway was collected for the year 1995 from IRTAD data. Using Dutch ratio's an indicative estimation of these accidents and deaths in EU countries per year was calculated.

Dutch data

In the Netherlands multiple accidents on emergency lanes had a share of 1.5% *injury accidents* on Dutch motorways and 8% *fatalities* (1992-1995). The older Dutch and UK figures were higher. For the *injury accidents* in both countries, 2.8% and for the *fatalities* resp. 9.5 and 10.7% was found. For the estimation of the proportion of such accidents in EU countries, is chosen for the recent Dutch figures.

Using these figures, we can conclude that at least 1000 (rounded up from 967) of such injury accidents take place each year on all motorways in EU-countries and about 300 (rounded up from 280) persons are killed. If we take into consideration that the Dutch accident rates are better than average in Europe, we can conclude that these estimation are minimal.

Data from the United Kingdom

In 1980 - 1982 a working group on accidents on hard shoulders in the United Kingdom carried out a study to the frequency, causation, and possible means of reduction of accidents involving vehicles using motorway hard shoulders. It was shown that the severity of these accidents was three times higher than the severity of other accidents on motorways.

This research resulted in three types of approaches to accident reduction on the hard shoulders: engineering, legislation, and behaviour. The group concluded the following:

As *engineering* measures mentioned are (advanced) road marking, surface maintenance and cable detection as a warning system for approaching drivers and the police. Owing to financial limitations, a implementation for these measures could be based on a required minimal level of traffic flow. In terms of cost-effectiveness there is no engineering counter-measure suitable for application over the whole network of roads.

Legislative measures and enforcement are considered and discussed as possible amendments to the Motorway regulations. Only a few amendments were concluded as positive: e.g. the use of four-way hazard flashers by vehicles halted on hard shoulders. Other amendments were judged as negative, for example: rendering obligatory immediate removal of stationary vehicles from

hard shoulders (suggested is that such obligatory actions could result in more delay in traffic than stationary vehicle themselves), defining 'emergency' in the Motorway Regulations and eliminating the regulation which legitimizes amateur assistance.

Also the compulsory use of a reflective red warning triangle is discussed; in some European countries the presence and use is compulsory. The working group was against such a regulation in the United Kingdom. Placement of the triangle in accordance with the Highway Code recommendation approx. 50-150 yards behind the vehicle, entails extra risk for the driver in walking back down the hard shoulder.

Influencing the driver behaviour gave some positive remarks: a) fixing notices on emergency telephone boxes and explaining their functions and b) revising the leaflet on motorway use to indicate the circumstances in which hard shoulders should, and should not, be used.

The Netherlands Accident study In the Netherlands, research was carried out in 1987 inspired by the death of some break-down service officers. The research of Mathijssen (1987) consisted of an accident and behaviour study. Included was also a literature study, but no studies were found about the estimation of the road accidents risk caused by vehicles situated on emergency lanes (and hard shoulders) of the motorways.

In relation with the accident study, at first the multiple accidents on emergency lanes were defined as follows:

- at least two (or more) road users involved in an injury accident on motorway emergency lanes;
- at least one of the involved vehicles (road users) was on, leaving, or entering the emergency lane (hard shoulder).

The number of deaths per 100 injury accidents for the multiple accidents on emergency lanes were 21.5 in contrast to the 6.3 death per 100 injury accidents of all the accidents on motorways.

The distribution of some characteristics of these multiple accidents were:

| | |
|--|-----|
| Darkness, no road lighting | 25% |
| Road works zones | 6% |
| Secondary accident (at location of primary accident) | 6% |
| Straight sections of the road | 95% |

Percentage of all of the multiple accidents on emergency lanes (N=171)

The distribution of some behavioural 'causes' of multiple accidents were:

| | |
|---|-----|
| Drive too much on the right side of the carriageway | 38% |
| Accidents with pedestrians | 17% |
| Skidding of the vehicle | 14% |
| Out of control | 7% |
| Wrong way joining the traffic from emergency lane | 6% |

Percentage of all of the multiple accidents on emergency lanes (N=171)

Crossing the marking strip

Also in the Netherlands, observations are carried out of the frequency of crossing the marking strip between the emergency lane and carriageway (Oldenburg, 1985). Distinction is made in the vehicle category, carriageway lane width, and dry / wet surface.

The following results were found with limited observations. Vans and trucks have two times more cross-overs if the lane width is 3.25 m instead of 3.5 m. Also the influence of a wet or dry surface is considerable; on a wet surface there are considerably more cross-overs, both for passenger cars as well as for vans and trucks, in comparison with a dry surface.

Crossing the marking strip can be dangerous. In the study of Mathijssen (1987) was found that about 20% of the stopped vehicles on the emergency lanes, were less than 1 m away from the marking strip.

3.1.3 *Investigations regarding vehicles stopping on emergency lanes*

Vehicles stopped on the emergency lanes are potential dangerous spots. A factor to calculate the risk for a collision with these vehicles standstill is the number of stopped vehicles on emergency lanes per 100 km motorway. So far as we know, only in the Netherlands has this been investigated. The first study is already 12 years old and carried out by SWOV (Mathijssen, 1987). The values, given with a contribution to the reason for the use of the emergency lanes are (both directions):

| | |
|-------------------------------------|-------------------------|
| Broken-down cars + service vehicles | 1.5 vehicles per 100 km |
| Road work zones related | 1.6 per 100 km |
| Others | 1.0 per 100 km |
| <i>Total</i> | <i>4.1 per 100 km</i> |

A second study has been carried out for SAFESTAR. The observations were performed in 1997 by SWOV.

A random sample of observations has shown that one had to drive an average of about 18 km to meet a broken-down car or other vehicle/obstacle on the emergency lane at one side of the motorway. This means 10.9 vehicles/obstacles per 100 km as average at both sides. Within this value, the influence of vehicles/obstacles at road work zones is large. These aspects will be considered in greater detail by the European ARROWS project.

In comparison with the value found in 1987, the number of vehicles/obstacles per 100 km found in 1997 had more than doubled. The influence of the daily traffic intensity is likely to be one of the reasons.

Average waiting time in the case of a broken-down car

Based on data from the road service of the Royal Dutch Tourist Association ANWB, calculations were made for the average waiting time along the motorway. The average waiting time found for technical help was 32 minutes; the average repair time was 23 minutes. Taking into account that the time to call technical service by using the alarm phone was about 5 minutes, we get as a very rough estimation a time of 60 minutes of average stay of a broken-down car on the motorway (plus 23 minutes accompanied by the service car). These are the average times. Of course the amount of time depends on hour of the day, day of the week, and month of the year.

Warning triangle.

In 1987 Mathijssen found that for only 3% of the vehicles stopped on emergency lanes, the mandatory warning triangle was placed. The following reasons for this very low percentage are given: 1) insufficient knowledge of traffic rules, 2) absence of emergency triangle in the car, 3) trouble to get out the car and to place the triangle, 4) fear of being run over while placing the

triangle, 5) doubt about efficiency of the triangle as a warning device, and 6) doubt about the necessity to warn other road users.

Work zones

The 4th Framework Programme of DGVII started in 1997 an Advanced Research on Road Work zone Safety Standards in Europe (ARROWS). ARROWS concerns the whole range of measures of applicable road work zone safety measures, including the use of emergency lanes of motorways.

Emergency lane as an additional lane during rush-hours

In order to obtain a better usage of the existing infrastructure, the Dutch Ministry of Transport is testing the possibilities to use the emergency lane as an additional lane during rush-hours. TNO has advised the Ministry (Theeuwes et al, 1995) concerning the necessary signalling of the experimental sections in use.

Bus on emergency lanes

As experiment, the use of emergency lanes by buses as additional lanes during the rush-hours, was investigated in The Netherlands in early 1990. An evaluation of these experiments show the following results:

- use of short sections of emergency lanes for buses does not increase the road accident risk when properly designed, prepared and organized;
- work out a proper signalling of such location using electronic warning boards.

The preliminary recommendations to be learnt from these experiments are:

- speed of buses should be reduced;
- additional reserve breakdown parking places should be made available along sections of emergency lanes;
- there is no data to estimate the impact on road safety of these experiments, measured in terms of road accidents;
- according to subjective estimations of bus drivers, passengers, and other involved drivers, the safety declined on the experimental locations.

For final conclusions more tests were recommended.

Recommendations

Despite the present international agreements on motorways the national standards and practice in European countries are different. The recent typology of TERN-motorways demand a harmonisation of these standards on significant parts of European motorways included in TERN.

A regular periodic check and monitoring of achievements in this harmonisation will be recommended. A randomized inventory of journey observations of a couple of hundred kilometres per country is proposed in order to produce a periodic report to the coordinating group Motorway Working Group of the Directorate General, DGVII Transport.

Also recommended is to gather information from the European countries about the experience with special use of emergency lanes, like:

- during the rush-hours;
- separated lane for buses;

- using a lane or two when the lanes in the opposite direction of the road are being reconstructed.

This data is helpful for preparing European standards.

Only little is known about the extent and the risk of multiple accidents on emergency lanes in European countries. One figure necessary to calculate the risk is the average number of stopped vehicles and obstacles per 100 km. The value found in the Netherlands (average 11 vehicles/-obstacles per 100 km on both sides) can be helpful as reference for other European countries.

At hazardous locations with a higher risk, some additional measures can be taken:

- rumble strips for marking the border between a carriageway and the emergency lane;
- widening of emergency lanes;
- information campaigns for road users about typical hazardous locations;
- application of lighting on motorways, especially on sections where emergency lanes or carriage lanes are narrow.

3.2. Express roads

SAFESTAR aimed at producing safety standards for express roads, with the intention of improving the unfavourable safety records of this road type. An extensive accident analysis, combined with an evaluation of decision making processes, expert interviews, and a literature review, form the basis for design recommendations.

Because of the limited amount of information and knowledge of safety effects of design variations on this road type, further research is recommended.

Research for this task has been carried out by SWOV and LNEC.

3.2.1 Express roads in TERN

Motorways and single carriageway ordinary roads are two main types of roads which exist in all EU Member States and which are known by all motorists. Most countries also have some sort of roads, which do not fulfil the design criteria of a motorway, but which are of a higher order than the ordinary single carriageway roads. These intermediate types of roads are sometimes classified under the name of 'express roads', but in the majority of EU Member States these roads do not occur as a separate category in the national road categorisation. In general, the safety records of this intermediate type of roads are bad, not only in comparison with motorways, but also in comparison with ordinary roads (Cardoso and Costa, 1998).

The development of TERN, the Trans-European Road Network, as set out in the 1993 Treaty of the European Union, aims to provide a road network for main international road travel, connecting all parts of the European Union. The largest part of the network consists of existing motorways. A substantial part, however, consists of roads which are non-motorways. Non-motorway links consist of ordinary roads and express roads. Ordinary roads generally have a traffic flow capacity of less than 5,000 vehicles per day. It is suggested that for traffic flow between 5,000 and 10,000/15,000 vehicles per day an express road may be the best solution, with the optimal traffic flow capacity depending on the exact characteristics.

The general characteristics of express roads are described by the Motorway Working Group Action Start in 'Standardisation of Typology on the Trans-European Road Network' (1994). The Working Group recommends that express roads should:

- have no urban sections;
- have no private access;
- do not permit parking and stopping on the carriageway;
- do not permit slow moving vehicles, bicycles, pedestrians or animals;
- have a minimum lane width of 3.5 m.;
- have edge line and central markings;
- have a head clearance of 4.5 m.;
- provide for emergency calling points;
- provide for service area's at a maximum distance of 100 km., directly accessible from the road, and with 24 hours refuelling possibilities;
- have an average daily traffic for single carriageway express road of 5,000 vehicles per day; for dual carriageway express roads 10,000/15,000 vehicles per day.

Express roads can be designed as single or dual carriageway roads. On dual carriageway express roads intersections can be both grade-separated or at-grade.

Outside urban areas, two road types with a traffic flow function can be identified, namely motorways and express roads. As indicated by the poor safety records of express roads in Chapter 1, motorways are preferred for road-network sections with a traffic flow function. Arguments other than those of safety, however, proved to be decisive factors in all countries studied.

An analysis of the arguments in the decision to build express roads in several EU-member states showed a very consistent image of the arguments and their relative weight. An express road is built or an existing ordinary road is upgraded when the (expected) traffic volume exceeds a particular number, when higher speeds are considered to be desirable, and when there are financial and/or environmental restraints to build a motorway. An economical cost-benefit analysis is applied in, for example, France and the UK. The argument of better accessibility to main economical centres alongside the road compared to motorways was always mentioned. Safety as an argument in the decision process was never mentioned, although some design standards and guidelines do refer to the need for uniformity and continuity in relation to the adjacent network for safety reasons.

In the Netherlands, the main reason for the existence of express roads is considered to be a financial one. Because of the high costs of motorway construction, cheaper express roads may be considered as a financially better solution, unless preconditions compellingly force the construction of a motorway. The preconditions on which it is decided to choose for a motorway or an expressway are formulated in so called Ministerial Road Plans. In these plans road sections of the national road network are assigned as motorway or as express road. The assignment is mainly based on:

- Function of the section within the entire road network: if a section has a less important traffic function in the network, the choice for a express road design is more likely.

- Traffic volumes: if traffic volumes or estimated traffic volumes exceed standards described in the national design guidelines, an express road is not a valid option and a motorway design has to be chosen.

Decisions on the Ministerial Road Plans are not made at the level of the Regional Departments, but at the level of the National Ministry of Transport. In the decision making process, all consequences have to be weighted. In this process the importance of safety (or the difference in safety between motorways and express roads) is often considered to be of less importance than costs, congestion, accessibility and reliability of the road network. One could say that the actual safety difference between motorways and express roads is not large enough to make it an important issue at this decision level.

The analysis of the decisions to build express roads in several EU-member states demonstrate that the choice for the sub-standard express roads will also be made in the future, as a result of which the express road will continue to play an important role in the Trans European Road Network. Replacing existing express road sections by the more expensive motorway sections, or planning for motorways rather than express roads, does not seem to be a realistic strategy.

3.2.2 *Improvements in cross-sectional design*

Because the express roads will continue to exist in the future road-network, strategies to improve the poor safety records of express roads have to be developed.

An important contribution is the formulation of uniform, safety based design guidelines. A problem in this formulation of design guidelines however, is the very small amount of research information on this road type. To overcome this problem in the short term, valuable information for the design of express roads can be derived from other, more or less comparable road types. Though not accurate and specific enough to use as a basis for the formulation of design recommendations or standards, the information can give some insight in possible safety effects, probable direction of effects, and estimates on the strength of the effects. Exact quantitative information in this study can therefore not be used directly for express roads. The lack of specific information on safety effects of design parameters on express roads stresses the need for further research. Information in this study can serve as a guideline in this future research.

Lane width

In a study of accidents on A-class roads in Great Britain (comparable to express roads as defined in SAFESTAR), the effects of variations in carriageway width were studied (Hughes et al., 1997):

- For dual carriageway sections an increase of one metre in main carriageway width resulted in a decrease of 56 % in the chance of an accident involving a vehicle joining the main road from an on-ramp.
- For single carriageway A-class roads, within the carriageway width considered in the model (7.0 - 21.2 m.), a one metre increase in carriageway width at a junction resulted in an estimated accident reduction of 5 %.
- For sections between junctions on single carriageway A-class roads, a one metre increase in carriageway width resulted in a 19 % decrease in accidents (range considered in the model was 7.1 - 11.5 m.).

The authors stress that the observed effects are not linear and that they are only applicable within the range of the model.

Based on the analysis of accidents on two-lane rural highways, Zegeer et al. (1981; 1987) concluded that accident rates generally decrease with increasing lane and shoulder width. Lane and shoulder width directly effect run-off-the-road accidents and opposite-direction accidents. Other accident types proved not to be directly effected by these elements. The accident rates Zegeer et al. found were approximately the same for 3.6 m. lanes as for 3.3 m. lanes, possibly indicating that the limit beyond further increase in lane width are ineffectual. Lane widths proved to have a greater effect on accident rates than shoulder width.

The evaluation of traffic accidents in Germany by Oellers (1976) led to the result that the frequency of accidents due to errors in overtaking, being overtaken, and changing lanes was higher on stretches with narrow traffic lanes (3.25 m.).

Hadi et al. (1995) estimated the effects of cross-section design elements on total, fatality, and injury accident rates for various types of rural and urban highways at different traffic levels. They concluded that significant relationships could be found between lane width and accidents for undivided highways and urban freeways. For other highway types, no such relationship could be identified. They indicate that for two-lane rural, two-lane urban, four-lane urban undivided, and urban freeways widening lane width up to 4.0 m., 3.7 m., 4.0 m. and 4.3 m. respectively could be expected to decrease accident rates. They furthermore indicate that the highest benefits due to lane widening were estimated for urban freeways, followed by four-lane undivided urban highways, followed by two-lane rural highways. For two-lane urban highways there was significant relationship between pavement width (lane width plus paved shoulder width) and accident frequency rather than between lane width and accident frequency when continuous representations of variables were used. The effect of lane width on accident rate for this highway type was lower than other highway types.

Accident analysis on express roads in Portugal by Cardoso and Costa (1998) proved that single carriageway express roads with lane widths greater than 3.50 m. had better accident records than roads with lower lane widths.

From the above-mentioned results one could get the impression that 'the wider a road is, the safer it is'. Michalski (1994) questions the validity of this hypothesis, based on safety research carried out in Switzerland. Results showed that increasing the single carriageway width to 8.5 - 10.0 m. decreased accident rates as well as the victim rates, but for widths between 12.0 - 14.0 m. both rates increased again. For motorways, widening a traffic lane over 3.5 m. causes no significant further improvement of the accident rates. The lane width of 3.5 m. can therefore be indicated as an optimum for motorways.

Shoulder width

Several studies (Hedman, 1990; Zegeer et al., 1988) show a decrease in accidents with an increase in shoulder width.

As noted by Hedman (1990), recent studies show a decrease in accidents with an increase in width from 0 to 2 m. Additional benefits for widths above 2.5 m. proved to be very small. Several authors have furthermore concluded that the effect of lane width on accident rates is greater than the effect of shoulder width.

Zegeer et al. (1988) concluded that non-stabilized shoulders, including loose gravel, crushed stone, raw earth, and turf, exhibit greater accident rates than stabilized or paved shoulder. The same conclusion was drawn by Armour (1984) who found that the accident rate of roads with unsealed shoulders was between three and four times the accident rate for roads with sealed shoulders. This was true for straight road sections and for road sections with curve or grade. An examination of accident description showed that losing control of vehicle in the gravel shoulder was a contributing cause in about 17 % of fatal accidents.

German comparative studies concerning motorways (Brühning, 1977) show that the motorways with an emergency stopping lane (often 3.0 m.) reduced the total accident rate by more than 15 %, when compared to rates on motorways with narrow paved shoulders.

Median

A median separates the traffic lanes in opposite direction, thus creating two separate carriageways. Elements of median design which, according to Zegeer & Council (1992), may influence accident frequency or severity, include median width, median slope, median type (raised or depressed) and presence or absence of a median barrier. Wider medians are considered desirable in that they reduce the likelihood of head-on accidents between vehicles in opposite directions. Median slope and design can effect rollover accidents and also other single-vehicle accidents (fixed object) and head-on accidents with opposing traffic. The installation of median barriers typically increases overall accident frequency due to the increased number of hits to the barrier, but reduces accident severity, resulting from a reduction or elimination of head-on collisions with opposing traffic.

A 1973 study by Garner and Deen in Kentucky compared the accident experience of various median widths, median types (raised vs depressed), and slopes on Interstate and turnpike roads in Kentucky (Garner & Deen, 1973). Highways with at least 9 m. wide medians had lower accident rates than those with narrower median widths. For wider medians, a significant reduction was also found in the percentage of accidents involving a vehicle crossing the median.

Median slopes of 4:1 or steeper had abnormally high accident rates for various median widths, while a higher accident severity and higher proportion of vehicle overturn accidents were found for medians which were deeply depressed. For median widths of 6 m. to 9 m., the use of a raised median barrier resulted in a higher number of accidents involving hitting the median and losing control. (Unfortunately no information was given on the severity of the accidents).

Climbing lane

The presence of a climbing lane on a two-lane (single carriageway) section can reduce the number of catastrophic overtaking accidents that occur due to the presence of opposing vehicles. Such accidents normally involve high-speed head-on or run-off-the-road accident types. On dual carriageway sections the purpose of climbing lanes is mainly to improve traffic operations. Safety effects are generally caused by the minimizing of speed differences on the adjoining lanes and thereby reducing the chance of rear-end accidents.

Hedman (1990) quotes a Swedish study which concluded that climbing lanes on rural two-lane roads reduced the total accident rate by an average on 25 %, 10 % to 20 % on moderate up-gradients (3 % to 4 %), and 20 % to 40% on steeper gradients. It was also observed that

additional accident reduction can be obtained within a distance of about 1 km. beyond the climbing lane.

Martin and Voorhees Associates (1978) found an overall reduction of accidents of 13 % due to the presence of climbing lanes in the UK.

Harwood et al. (1988) quote a California study by Rinde (1977) at 23 sites in level, rolling, and mountainous terrain where accident rate reductions were found due to the passing lane installation of 11 % to 27 %, depending on road width. When the sites in mountainous terrain were excluded from the analysis, accident reductions of 42 % were found for the level terrain sites as well as for the rolling terrain sites.

3.2.3 *Conclusions and recommendations*

For both single and dual carriageway express roads, a lane width of 3.5 m. can be recommended.

Research on the effects of lane width on motorways and low volume highways resulted in an optimum lane width of 3.5 m. to 3.6 m. With similar results for road-categories just above and below the express road category, it can be safely assumed that this value will also be a safe standard for express roads.

Though the positive effect of lane width is greater than the effect of shoulder width, several studies have concluded that the presence of shoulders contribute significantly to traffic safety. The presence of paved shoulders can therefore be recommended for both single and dual carriageway express roads. Research however does not indicate an unequivocal value for the optimum shoulder width. Recommendations on the exact shoulder width can therefore not be given in this report. Local situation and traffic behaviour as well as shoulder widths differ widely in the various European countries.

For determining the shoulder width, the method used in the Dutch guidelines (ROA, 1992/1993) seems valuable. Based on the dimensions of the width of a truck of 2.5 m., a shoulder width of 3.0 m. to 3.5 m. is recommended. A stationary truck on the shoulder can be passed safely and without influencing traffic operations seriously. Given the lack of empirical data and equivocal conclusions, these dimensions can only be seen as 'best practice'.

The separation of opposing traffic with a median strongly improves traffic safety. The usually very severe head-on accidents are fully excluded.

The width of the unpaved median is dependent on the location of the median crash barriers. Accident barriers are not essential if there is no risk that the median may be crossed. This width is assumed to be approximately 20 m. Because such a width will generally not be feasible in practice, medians are normally equipped with accident barriers. Safety generally improves with widening of the median. The greater the distance from carriageway edge to median barrier is, the greater the possibility will be that an off-road driver can recover safely (without hitting the median barrier).

Slopes and obstacles in the median should be avoided (or protected).

Because of the considerable improvement of traffic safety, climbing lanes must be recommended on upgrade sections on single carriageway express roads. Even on moderate upgradients (3 % to 4 %), climbing lanes can reduce the accident rates.

On dual carriageway express roads, the provision of climbing lanes is dependent on the steepness of the gradient, the number of heavy trucks, and the possibility of slow moving trucks reducing speeds of other vehicles.

3.3 Rural roads

The effects of different kinds of cross-sectional designs on two-lane rural roads have been studied by reviewing existing literature and by analysing Finnish and Danish accident data. The study concentrated on the safety effects (especially injury accidents) of different kinds of cross sections.

Experiments were carried out Portuguese and Swedish two-lane rural roads with alternative countermeasures. These experiments have been evaluated.

3.3.1 Accident experience

Although the risk of injury accidents per kilometre driven is higher on urban roads, the risk of a fatal accident is considerably higher on rural roads. Accident analysis in Finland for instance show that about 70% of the injury accidents and 80% of the fatalities occur on two-lane rural roads. Accident analysis in other European countries show comparable results.

The two most dominant accident types of serious accidents are head-on accidents and run-off-the-road accidents. Both accident types indicate the important role of the cross-section design and cross-sectional measures in the safety of rural roads.

The accident analysis in Finland and Denmark focussed mainly on head-on accidents and run-off-the-road accidents.

The roadway variables possibly associated with these accident types include lane width, shoulder width and type, roadside condition, terrain condition and traffic volume. Also, the presence of unprotected road users can have an effect on cross-section safety.

On two-lane 80 km/h rural road stretches (also 100 km/h in Finland), 50% of the injury accidents in Finland were run-off-the-road accidents and 23% were head-on accidents. In Denmark, the percentages were 31% and 16% respectively.

In fatalities, head-on accidents covered 55% in Finland and 39% in Denmark. The percentages for run-off-the-road fatal accidents were 20% in both countries.

Based on the data of the Accident Investigation Teams in Finland, it was possible to find some differences in the causes for head-on accidents and run-off-the-road accidents. Head-on accidents had more often several explaining factors leading to an accident. As for the run-off-the-road accidents, it was often possible to find one strong factor affecting the occurrence of an accident (e.g. paroxysm, alcohol, falling asleep). In head-on accidents, bad weather and bad road conditions easily led to driver errors.

If there is one major factor leading to the occurrence of an accident, the possible countermeasures are somewhat limited. Most of these factors cannot be eliminated easily (e.g. paroxysm, alcohol).

Run-off-the-road accidents

Accident analysis in Denmark proved that speed, wheels on the verge or soft shoulder, objects on or along the road and alcohol were frequent causes of accidents and determining factors of the severity of the accidents.

High speeds (in relation to the road alignment or to weather conditions) were described as a cause in at least 23% of the run-off-the-road accidents. Entering the verge with the right hand wheels of the car was specifically mentioned in 19% of the accidents.

Study of the data of the Accident Investigation Teams, for all victims in fatal run-off-the-road accidents on two-lane rural road stretches showed the following results:

- Run-off-the-road accidents accounted for only 23% of the number of victims.
- Almost 60% of the victims resulted from run-off-the-road accidents on straight or almost straight road sections.
- Relatively large numbers of run-off-the-road victims occurred on straight or almost straight road sections, where the driver had fallen asleep.

According to earlier in-depth studies in Finland (e.g. Räsänen, 1997), almost 80% of fatal run-off-the-road accidents could be attributed to a single explanatory variable. According to this Finnish study, the drivers' contribution to these accidents can roughly be divided into four categories: alcohol, driving abilities (vehicle handling, perception, prediction), driver inattention, and suicide.

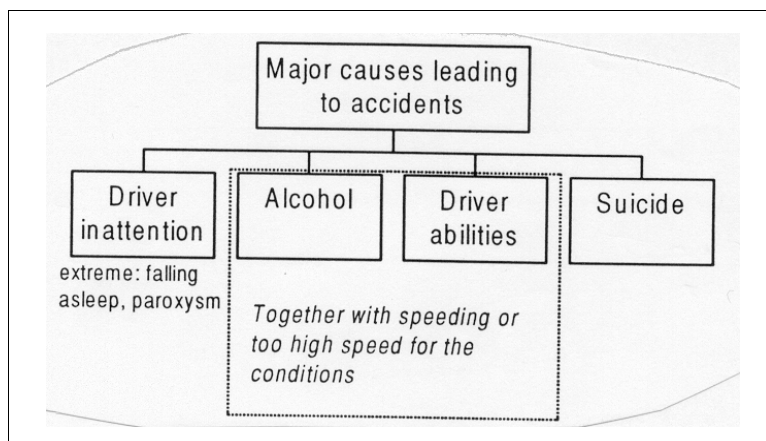


Figure 3.1 *Major causes in run-off-the-road accidents*

Head-on accidents:

Study of accident causes of fatal head-on accidents on Danish two-lane rural roads, showed that causes were mentioned in about 50% of the accidents. Causes which were often mentioned were high speeds, overtaking manoeuvres, and wheels on the verge or soft shoulder (resulting in overcorrecting manoeuvres). Driving at a speed too high for the road alignment or weather and road conditions, and thereby losing control over the vehicle, was stated in many of the accidents.

A recently published Danish report (AVU, 1997) showed that the most frequently occurring accident factors were high speed and driving under the influence of alcohol, narcotics and/or

medicine. Other mentioned causes were: errors in connection with overtaking and reckless driving, improper evasive actions, inattention towards the road (e.g. using mobile telephones), and tiredness.

Study of the Accident Investigation Teams data for all victims in fatal head-on accidents on two-lane rural road stretches showed the following results:

- Head-on accidents accounted for 77% of the total number of victims.
- Overtaking proved to be a quite rare event in head-on accidents (10% of the victims), whereas one would expect this to be a more important accident cause.
- Almost 90% of the victims in head-on accidents resulted from an accident occurring on straight or almost straight road sections.
- Head-on accidents were more often connected to bad weather conditions, especially slippery roads, compared to run-off-the-road and other accidents.

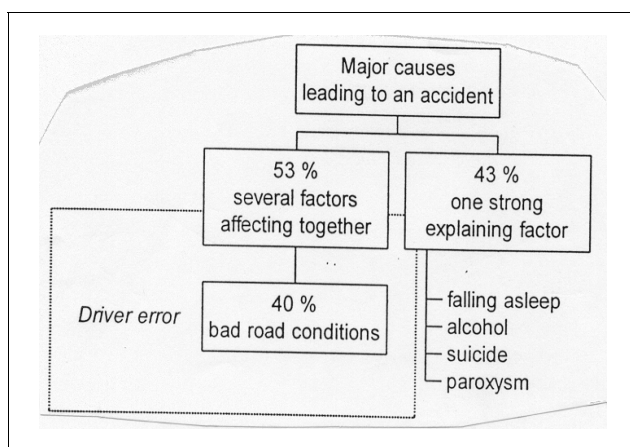


Figure 3.2 Major causes in head-on accidents

Two major things that distinguish head-on accidents from run-off-the-road accidents were:

- Head-on accidents had more often several explaining factors leading to an accident. Weather and road conditions played a more important role in head-on accidents.
- In contradiction with run-off-the-road accidents, alcohol was not involved in head-on accidents more than in accidents on average.

3.3.2 Effects of cross-sectional design

Two-lane rural roads include many different types of road, ranging from traditional, winding roads to modern high quality roads with gentle curves and full cross-sections. Thus, undivided rural roads can have considerable variation in dimensions of traffic lanes and shoulders, not to mention the variety in roadside characteristics.

Of the cross-section design parameters, only the concept of lane width is fairly unambiguous between different countries. Other design parameters, such as shoulder width and type, or sideslope design, vary widely in design practice.

In the accident analysis in Denmark, accident risks were calculated for rural roads of different road and shoulder widths. The main conclusions of this study were:

- The average risk for run-off-the-road accidents was somewhat lower on wider roads.
- The average risk for head-on accidents was not found to be influenced by the road width.
- On 6 m. and 7 m. roads, the average risk for run-off-the-road accidents was lower on wider paved shoulders.
- The average risk for head-on accidents was not found to be influenced by the paved shoulder width.
- For all other accidents, the average risk in general was lower on wider roads and roads with wider shoulders.
- A previous Danish study (Danish Road Directorate, 1996) showed that about 70% of all obstacles in the accident were situated at a distance of 3 m. or less from the road, and that most of the accidents might have been avoided if the distance between the edge line and the obstacle was 9 m. or more.
- In fatal accidents in Finland, speeds were often high, judging from the fact that vehicles in more than 50% of the accidents were extensively or totally destroyed. Almost all of the run-off-the-road accidents took place quite close, inside 7 m, from the road edge.

According to these Danish results, it can be concluded that in general the upgrading of the road does not seem to effect the average risk for head-on accidents.

These results are however in contrast with results of studies in the USA, Germany and Australia, where widening of both lanes and shoulders showed a decrease in head-on accidents.

Driving lane

Studies in the USA and Germany (Zegeer, 1987; Zegeer, 1995; Brannolte et al. 1993) prove that the number of accidents generally decreases with increasing lane width. Accident rates did not decrease any further for lane widths of 3.3 - 3.6 m., possibly indicating the lane width beyond which further widening were ineffectual. Lane widths of 3.3 - 3.6 m. (Brannolte et al. mention 3.5 m.) can be seen as an optimum.

Zegeer et al. (1987) quantified the effects of lane width on highway accident experience, based on an analysis of data for nearly 8000 km. of two-lane highway from seven states. Results showed that the accident types found to be most related to cross-section features include run-off-road, head-on and sideswipe accidents. Lane widening of 0.3 m. was found to reduce these related accidents by 12%, 0.6 m. by 23%, 0.9 m. by 32% and 1.2 m. by 40%.

The results conclude to be valid for two-lane rural roads with lane widths of 2.4 to 3.7 m. and ADT's of 100 to 10,000. The study was reported to control for many roadway and traffic features, including roadside hazard, terrain and average daily traffic. However, to fully eliminate the effects of all other variables is impossible, and therefore the effects of lane widening may be overestimated.

Shoulder

In general there is no agreement in EU countries on the paved shoulder width of non-motorways.

Situations vary from non-motorways without shoulders to non-motorways with wide shoulders. As a result, pavement width can vary from 6 m. or less, to 11.5 m.

These variations partly reflect the fact that there is no consensus on the safety effects of the shoulders.

A Danish study (Vejdirektoratet, 1984) concluded that for carriageway widths of 6.5 to 8 m., a paved shoulder increase from 0.2 m. to 0.5 m. showed a significant reduction of accident risks for vehicle accidents by about 25% and for pedestrian and cycling accidents by 40%. The effects of further increase in shoulder width (≥ 0.9 m.) was uncertain, but indicated no effect on vehicle accidents and possibly a further reduction of 20% in pedestrian and cycling accidents.

In Germany, Brannolte et al. (1992) detected that two-lane roads with shoulders had an approximately 10% lower accident rate compared to similar roads without shoulders. The difference in accident cost rate was greatest when turning and crossing accidents were included in the comparison.

In the USA, Foody and Long (1974) found that the mean accident rate for stabilised shoulder sections was significantly lower than for sections of unstabilised shoulders. Particularly, the results indicated that shoulder stabilisation or paving was quite effective in reducing run-off-the-road accidents on narrow carriageways, typically 6 m. or less in width, but had only little effects on road widths of 7.2 m. or more.

Several authors (Zegeer, 1979/1987/1995, Brannolte et al. 1993, Edholm & Roosmark, 1969) found decreasing accident rates with increasing paved shoulder widths. An optimum value for the shoulder widths is not determined unambiguously, but a total pavement width of 10 m. (3.5 - 3.7 m. wide lanes and paved or stabilised shoulders of 1.3 - 1.5 m.) is mentioned as the pavement width beyond which further widening does not improve safety. Pavement widths greater than 10 m. could possibly encourage higher speeds and more careless driving. In general, 'overwide' roads have proven to cause increasing accident rates.

Pavement width

In Sweden, the effects of pavement width on the accident rates have been modelled from the 1970's (Brüde & Nilson, 1976, Brüde & Larsson, 1977). The model differentiates between three classes of alignment, namely:

- mainly straight sections with slight gradients;
- comparatively large curve radii and slight or steep gradients;
- small curve radii and slight or steep gradients.

For all 90 km/h roads the accident rate decreased with pavement widening up to about 10 m. For further increase of the pavement width, the accident rates increased in the third alignment class (small radii and slight or steep gradients).

In Finland, Peltola (1995) concluded that on main roads, the risks for personal injury and fatality appeared to be lower on wide pavements (medium wide: 8.1-9 m.; wide: over 9 m.). The results were equal for ADT's over and under 6000 vehicles per day. However, on other than main roads, the fatality risk seemed higher on wider pavements. Increase in risk was attributed to more severe single-vehicle, overtaking and head-on accidents.

Carlsson and Lundkvist (1992) and Brüde and Larsson (1994) studied the safety effects of an increase in lane width (from 3.75 m. to 5.50 m.) and a simultaneous reduction of shoulder width (from 2.75 m. to 1.00 m.). The results showed that lateral positioning was changed so that passenger cars were positioned further to the right of the roadway. Furthermore, the

variance of the lateral position was increased. On typical 13 m. wide roads, the severity of accidents increased in connection with the widening of the driving lane, but on express roads the cross-sectional change reduced the accident risk. Due to small accident counts clear conclusions were not drawn.

Later, in 1996 Brüde and Larsson compared existing roads with wide lanes and narrow shoulders with remaining roads of the same type but without wide lanes (having wide shoulders instead). The accident rate, injury consequence and injury rate were almost the same for roads with and without wide lanes.

However, there were differences in accident types. Wide lanes had a larger proportion of single vehicle accidents, but instead fewer rear-end, turning and crossroad accidents. It was concluded that wide lanes are not a practicable way of finding less expensive traffic safety alternatives to motorways.

In Germany, Brannolte (1993) also studied the effects of overwide rural roads with 5.25 m. lane width. Compared to a typical 3.75 m (or 3.5 m.) lane width, and 2 m. (1.5 m.) unpaved shoulder width, the accident rates and accident cost rates were higher on overwide roads.

Roadside design

According to Ruyters et al. (1994) in most European countries approximately one quarter of all casualties is killed in accidents with obstacles. Obstacles by the roadside (e.g. columns and trees) affect the accident risks and especially the accident severity. To reduce the number of collisions with obstacles, obstacle free zones are recommended. Based on accident research, widths of the obstacle free zone from 7 m. to 15 m. are recommended.

A Danish study (Danish Road Directorate, 1996) showed that about 70% of all obstacles in the accident were situated at a distance of 3 m. or less from the road, and that most of the accidents might have been avoided if the distance between the edge line and the obstacle was 9 m. or more.

In fatal run-off-the-road accidents in Finland, almost all of the accidents took place quite close, inside 7 m, from the road edge.

Zegeer (1988 and 1992) proved that on slopes steeper than 5:1, the risk of rollover accidents increases. Because rollover accidents are known to be severe, sideslopes steeper than 5:1 are strongly advised against.

Recommendations

Although not all results and recommendations are completely unequivocal, the following dimensions for cross-section design can be recommended:

Lane widths on two-lane rural roads should preferably be about 3.5 m.

The presence of shoulders is recommended because of the positive safety effects. The recommended width of the shoulder is between 1,3 m. to 1,5 m., resulting in a total pavement width of approximately 10 m.

Sideslopes steeper than 5:1 are not recommended, because of a significant higher severity of accidents with vehicles that run off the road.

Recommended values for obstacle free recovery zones differ widely in the studies used, and vary between 3 m. and 15 m.

3.3.3. *Effects of alternative countermeasures*

If accidents are caused by many factors (e.g. head-on), affecting one factor could have potential in preventing the occurrence of an accident. However, as the factors are many and accidents do not seem to accumulate into black spots, preventive measures should be very extensive or general, and probably also expensive. Costlier solutions can be justified on high volume main roads where most head-on fatalities occur, as the expected accident reduction can be predicted to be quite significant.

If an accident has one strong explanatory factor (e.g. run-off-the-road), possible countermeasures against the cause of the accident are somewhat limited. Many such factors cannot be eliminated by road design (e.g. seizure, stroke). However, there are potential measures for e.g. increasing driver alertness. The consequences of these accidents can yet be minimised.

In general, means of affecting severe accidents fall into two categories: either preventing the cause (i.e. preventing one or several contributing factors to an accident) or reducing the severity of an accident where conditions for an accident exist.

It appears that road design measures available for preventing the causes of severe accidents are fairly limited, and new ideas should be encouraged. Therefore every potential measure should be considered carefully. Furthermore, the fact that one might affect only the consequences should be accepted.

It is estimated that the median barrier eliminated or greatly reduces the fatal outcome of head-on accidents on two-lane roads. However it will possibly create a new hazard on the road. By now (ETSC, 1998), it has been estimated that median barriers will increase accident rates by 30% even though they reduce accident severity.

Several case studies on the effects of different types of median separators were carried out in the Safestar project. These case studies were conducted in Sweden and Portugal.

Behavioural studies were carried out with an instrumented car to evaluate the safety potential of the separators, with an unobtrusive microscopic observation of the test drivers.

Because of the short period since the implementation of the test sections, accident data are not available yet.

The tests in Portugal and Sweden will be discussed separately.

Portugal

Different types of separation of different directions of traffic on narrow four-lane roads were tested in the south of Portugal (Cardoso, 1998), with the use of an instrumented vehicle.

Tested were a concrete barrier, plastic delineators and a dual centre line.

The test route was 13.5 kilometres long. The selected four lane road was 14 m. wide (3 m. wide driving lanes and 1 m. wide shoulders).

Special attention was given to the driving behaviour in the left lane. Driving speeds and lateral position of the test runs were analysed.

The distance to the left edge line proved to be significantly greater for the more solid types of median separations. This distance to the left edge line was 0.6 m. for a dual centre line, 0.7 m. for plastic delineators and 0.8 m. for a concrete barrier

On the concrete separator sections the mean speed was 92 km/h, on the sections with a double line the mean speed was 80 km/h, and on the sections with plastic delineators the mean speed was 78 km/h. The speed differences were not statistically significant, and there proved to be no relation between speed and distance to the left edge line.

Costs per kilometre were 35,000 ECU for plastic delineators, 2,000 ECU for a dual centre line, and 36,000 ECU for a concrete barrier.

Sweden

In a Swedish project measurements were carried out on an experimental road in Gävle-Axmartavlan. test drivers drove along a test section with six different cross sections in an instrumented vehicle.

The following cross section types were studied:

- Two lane road with wide shoulders (total width 13 m.); speed limit 90 km/h.
- 2+1 road without median barrier; speed limit 90 km/h.
- 2+1 road with median barrier; speed limit 90 km/h.
- Wide two lane road (5.5 m. driving lanes and 1 m. shoulders); speed limit 110 km/h.
- Typical motorway.
- Narrow motorway (23 m.).

Speed measurements gave the following results:

| Road type | Standard deviation for speed of individual drivers (kn/h) | Standard deviation for mean speed (km/h) | Mean speed (km/h) |
|------------------------------|---|--|-------------------|
| Typical two-lane road (13 m) | 10,6 | 13.0 | 89.2 |
| 2+1 without median barrier | 12.2 | 14.9 | 91.9 |
| 2+1 with median barrier | 12.0 | 15.8 | 91.3 |
| Wide-lane road (13 m) | 12.6 | 15.3 | 97.8 |
| Typical motorway | 8.8 | 12.6 | 105.0 |
| Narrow motorway | 10.6 | 12.2 | 102.1 |

91.9: average for two-lane road sections

Table 3.1 *Mean speeds and standard deviations for the speeds on different types of roads*

After driving the drivers were asked to fill in a questionnaire. The answers were given on a five-point scale (1=bad, 2= not so good, 3=good, 4=very good).

To the question “How did you experience the road design?”, drivers gave 2+1 roads with and without a barrier as well as typical two-lane road sections an average rating of 2.5.

Narrow motorways were given a rating of 3.9, and wide two-lane road section were give a rating of 2,6.

To the question “How did you experience overtakings?” drivers gave an average rating of 2.9 for 2+1 roads both with and without a barrier. Two-lane roads got a slightly lower rating of

2.4. Wide two-lane roads were rated 3.0. Narrow motorways were experienced to be better (4.0) compared to other road types in the study.

Total costs for a 14 km Gävle-Axmartavlan experiment road (2+1 road with cable wire) were 3.5 million ECU which is roughly about 250 000 ECU per road kilometre. Individual expenses per road kilometre (or per unit) were as follows:

- cable wire 27 000 ECU,
- road markings together with traffic signs 19 000 ECU,
- widening stabilised shoulders together with 1:6 sideslope 85 000 ECU,
- pavement 66 000 ECU,
- parking areas 108 000 ECU each (total 2).

4. SAFETY DEVICES

4.1 Motorways and express roads: criteria for safe roadsides in relation to the installation of safety barriers (steel and concrete)

4.1.1 Introduction

To protect occupants of vehicles that leave the road from serious injuries, safe roadsides and medians are important. Free-zones, safety barriers, and impact attenuators are effective to realising this.

The CEN standards for safety devices, that are currently being developed, ensure the effectiveness of these devices, but say nothing about the road characteristics and circumstances in which they should (or should not) be applied.

This research aims to define criteria for places where safety devices are necessary. This is based on a general design philosophy for safe shoulders on motorways (and express roads), and based on design criteria for safety devices.

There is also a need for criteria to chose between steel and concrete barriers; the containment level of barriers will be a part of these criteria.

The target groups of these criteria are the road authorities in the TERN-framework, national road authorities in the European countries, authorities in transport departments, and (technical) staff responsible for road design and/or safety devices. More uniformity concerning safe shoulders on European roads will be the final goal.

Methods used

The research was carried out by means of a literature study included the national European standards. Furthermore, a questionnaire was prepared and sent to European institutes and ministries. This questionnaire contained, for instance, questions about national standards and/or criteria for the use of safety barriers, and accident data on motorways and express roads where safety barriers were involved. There was also a request to send copies of recent research reports concerning these subjects and in particular about cost-benefits. The European accidents were completed with data from an accident study carried out by SWOV.

Data from European countries, but also from the United States were analyzed for preparing a proposal for standards and strategies for EU-countries.

Questionnaire

The questionnaireA questionnaire for safety barriers on motorways and express roads was made and sent to all specialist of European countries.

The following subjects were asked about:

- * national standards and/or criteria for making the decision to locate safety barriers
- * the width of the obstacle-free zone, if there is no need for a safety barrier;
- * containment levels of the national barrier construction types;
- * presence of safety barriers with a distinction in steel and concrete (rough estimation);
- * accidents on motorways and express roads where safety barriers and off-the-road accidents were involved; accident data were asked with the following characteristics: number of injury accidents and number of fatalities and injured persons;

- * copies of recent research reports concerning safety barriers and particularly the differences between steel en concrete barriers, together with aspects such as costs, accidents, and cost-benefits.

Questionnaires were sent to 16 European traffic safety institutes or ministries; 13 questionnaires were completed, a response of approx. 80%. In some cases when a country did not give any data on a subject, we filled in the missing value based on the literature resource. It seems that most of the countries have standards both for motorways and express roads.

From data on injury accidents with safety barriers on motorways from some European countries, it seems, however, that erecting safety barriers is not always an absolute safe solution. Accident data showed that approximately 20% of the injury accidents on motorways was the result of a collision with a safety barrier.

4.1.2 *Roadside*

Attention has to be paid to the reduction of the high percentage of injury accidents with collisions with safety barriers and obstacles. The following line of action for creating a concept of a safe roadside is general accepted. The list is similar to the strategy used in the United States called 'create forgiving roadside'.

1. a shoulder without obstacles (and without safety barriers);
2. a shoulder with safe slopes;
3. a shoulder with fixed objects that yield easily upon collision;
4. a shoulder with accident cushions;
5. a shoulder with an effectively functioning safety barrier.

From the list of five possible solutions, the first four can be qualified as the best. The next best is the erection of safety barriers; this subject will be extensively discussed.

Owing to the systematical research carried out in Europe concerning this list of five possible solutions, much research is quoted from investigations carried out by SWOV under the authority of the Ministry of Transport and Public Works. In addition, research and data from standards from other European countries is mentioned.

A shoulder without obstacles

The question that immediately rises when discussing an obstacle-free-zone is how wide this zone should be. Every report beginning with this topic refers to American research from the 1960's and 70's. Since that time, as far as we know, hardly any more studies on this subject have been carried out in the United States. Although these studies were extremely valuable and have been used as a guiding principle in many European countries, their figures are based on the American situation. Two factors in these studies which differ considerably from the current European situation are the differences of vehicle mass and driving speeds.

The only known study carried out in Europe into a desirable width for an obstacle-free-zone was done in the Netherlands in the 1980's. This study involved road sections lined with rows of trees; these rows being located at various distances from the edge of the road. What this research establishes is the relationship between the accident ratio and the distance that vehicles

travel onto the shoulder when an accident occurs. This ratio is the number of accidents involving trees as opposed to the number of accidents not involving trees.

For *motorways* in the Dutch study it was found that when trees are planted at a distance of approximately 10 metres from the road, 10 out of the 100 accidents occurred with trees (figures based on a significant regression curve). The distance is measured from the marking line of the right-hand side traffic lane.

For *single-lane highways* (in some cases also express roads) 10 out of the 100 accidents occurred with trees planted at a distance of 7 metres from the road. The distance is measured from the border line on the right traffic lane. For the Dutch Ministry of Transport and Public Works these values were used for preparing standards.

When these distances of obstacle free zones were compared with the values of the standards of other European countries, agreement was found. The next table gives these values based on the mentioned questionnaires.

| Country | Motorway: width obstacle free-zone (m) | Express roads: width obstacle free-zone (m) |
|-----------------------|--|--|
| Belgium Wallonia | 4.5 | 3.75 |
| Czech Republic | 4.5 | 4.5 |
| Denmark ¹⁾ | 9 | 3 (9 m if $v \geq 90$ km/h) |
| Germany | 6 (10 if dangerous zone) | 4.5 (7.5 if dangerous zone) |
| Greece | 9 (19 near railway roads) | 9 (19 near railway roads) |
| Finland | 7 | 5.5 - 6.5 |
| France | 10 | 8.5 |
| Netherlands | 10 (if $v=120$ km/h: 13 m) | 6 |
| Norway | 6 (if ADT $\geq 15,000$) | 5 (if ADT is high) |
| Portugal | 3.5 | 3.5 |
| Sweden | 10 (if $v = 110$ km/h) 9 (if $v = 90$ km/h) 7 (if $v = 70$ km/h) | 10 (if $v = 110$ km/h) 9 (if $v = 90$ km/h) 7 (if $v = 70$ km/h) |
| Switzerland | 12.5 | 5 |
| United Kingdom | 4.5 | 4.5 |

- 1) In Denmark, the width is in discussion as a result of an audit concerning the design of the roadside as example. The intention is that the process will be based on effectiveness studies.

Table 4.1 *The width of the obstacle free-zone based on the following question on the SAFESTAR questionnaire 'What is the width of the obstacle free-zone if there is no need for a safety barrier?'*

A shoulder with safe slopes

United States

In the United States graphs have been developed with as basis that slopes with an angle of 4:1 and flatter are recoverable. Vehicles on recoverable slopes can usually be stopped or steered back to the roadway. Slopes steeper than 3:1 are critical and are usually defined as a slope on which a vehicle is likely to overturn.

The Netherlands

The only study for slopes ever carried out in Europe has been an investigation by SWOV. Mathematical simulations formed the basis for this research. The simulation results have been verified by using twelve full-scale tests on slopes with gradients of 2:1 and 4:1. From this study it was found that the radius of curvature at the top of the slope was of great importance in preventing the wheels from leaving the ground. For declining slopes, therefore, the radius of curvature may not be any smaller than 9 metres, but should preferably be 12 metres. With a gradient of 4:1, the vehicle stays in good contact with the ground, but steering manoeuvres are not helpful in gaining control. If the driver wants to be able to get the vehicle on the slope under control, a gradient of at least 5:1 is necessary for high slopes (e.g., 5 metres). For lower slopes (approx. 2 metres), a gradient of at least 6:1 is required. Ascending slopes were also studied by SWOV by using simulations of braking and steering manoeuvres. It was found that the radius of curvature at the foot had to be at least 4 metres, and that a gradient of 2:1 or gentler would be acceptable.

United Kingdom

In United Kingdom safety fences should be installed at trunk roads where speeds of 50 mph or above are allowed, in the following situations:

- on the top of an embankment with a height of 6 m or more;
- on other embankments where there is a road, railway, water hazard and others features at or near the foot of the slope;
- on the outside of curves less than 850 m radius on embankments between 3 and 6 m in height.

France

On motorways safety fences are prescribed if the height of the top is more than 4 m and 1 m if the area at foot level is dangerous with a length of at least 30 m. Fences are not necessary if the slope is 'soft', i.e. an angle of 1 : 4 or more. Motorways in South France must be provided with a safety fence if the slope height is between 2.5 and 4 m.

Germany

For the German motorways a division is made into the longitudinal road radius and the distance of the slope to the edge. If the outside radius is more than 1,500 m, safety barriers are required if:

- * a slope of < 8:1 at a distance of less than 6 m (10 m)
- * a slope of 8:1 to 5:1 at a distance of less than 8 m (12 m)
- * a slope of > 5:1 at a distance of less than 10 m (14 m).

Numbers between brackets means that, in the case of a very dangerous zone at the foot of the slope (for example deep water), the distance has to be increased.

If the outside radius is less than 1,500 m, add 4 m to the given distances (and 2 m for the numbers between the brackets).

For the German undivided roads with an outside radius of more than 500 m, the dimensions, if safety barriers are required are:

* a slope of < 8:1 at a distance of 4.5 m (7.5 m)

* a slope of 8:1 to 5:1 at a distance of 6 m (9 m)

* a slope of > 5:1 at a distance of 8 m (12 m).

If the outside radius is less than 500 m, add 6 m at the given distances (and 4 - 5 m for the numbers between the brackets).

Switzerland

A graph is given of the relation between slope height and the necessity to install a safety fence. For motorways: it ranges from a flat shoulder with a obstacle free-zone of 12.5 m to a slope with a height of 10 m with an obstacle free-zone of 27.5 m.

For undivided roads the range is: from a flat shoulder with a obstacle free-zone of 5 m to a slope height of 7 m with an obstacle free zone of 20 m. A slope angle is not given.

Denmark

The criteria in Denmark are based on the Dutch mathematical study.

Sweden

In Sweden a slope angle of 5:1 for downwards slopes is preferred.

Shoulder with fixed objects that yield easily upon collision

If a fixed object is made to yield, it can be placed in an obstacle-free zone without safety barriers. To reduce the impact severity for cars an appropriate breakaway device can be used. Breakaway supports refers to all type of sign, luminaire, and traffic signal supports that are designed to yield when hit by a vehicle. The release mechanism may be a slip base, plastic hinges, fracture elements, or a combination of these.

In the United States criteria to determine if a support is considered as 'breakaway' are described in 'Standard Specifications for Structural Support for Highway Signs, Luminaires and Traffic Signals'. The CEN is preparing standards for testing fixed objects (Passive safety of support structures for road equipment).

Examples of collision-safe fixed objects for the European situation are:

- aluminum lighting poles with a length of 10 metres and smaller, and steel poles with a slipbase; a deformable (patented) steel lighting pole developed in Sweden in the 1970's. NB. In Sweden roadside safety experts are trying to change the policy to locate lighting poles on the outside of curves onto insides of curves.
- a telephone box on a thin pole that bends forward and does not break off during a collision, thus preventing the pole from flying through the windscreen.
- signs on thin poles that easily bend during a collision; larger direction signs on thin poles in an A-shape.
- drainage features such as culverts and ditches have to be constructed with flattened sides in such a way that these constructions are traversable.

Although fixed objects probably present more of a danger for riders of motorcycles than for motorists in the case of an off-the-road accident, a shoulder with solitary obstacles is much to be preferred, in terms of motorcyclist safety, above a shoulder that is completely shielded by a safety barrier.

Shoulder with crash cushions

If solitary rigid obstacles along a shoulder cannot be removed, they can be shielded with a crash cushion. Crash cushions are applied on motorways in mainly two different situations: in pointed areas at exits (often at the beginning of a safety barrier) and on shoulders to shield single objects. If crash cushions have been hit head-on, the vehicle usually remains within the shoulder so that it forms no danger for other traffic. In the case of a side impact, most types of crash cushions function like a safety barrier.

Different European countries have their own type of crash cushion (Italy, United Kingdom, Germany and the Netherlands). Most accident experience has been gained in the Netherlands because the first crash cushions were located in 1982. In 1989 an evaluation study was carried out at a moment that at 170 locations, crash cushions were installed. The study dealt with 97 collisions with the crash cushion. Only 6 collisions resulted in (slight) injuries. At this moment more than 350 crash cushions are installed in the Netherlands.

Shoulder with safety barriers

In the concept of a safe roadside, protecting the roadside (shoulders and median) with safety barriers is the least safe solution. An effectively functioning safety barrier prevents a vehicle from leaving the roadway and striking a fixed object or terrain feature that is considered more hazardous than the barrier itself. But as already shown, a collision with a safety barrier is never free from the risk of injuries for the occupants of the colliding vehicle, as well as for other road users.

The requirements applying to safety barriers are:

1. The effective guiding of vehicles that have run off the carriageway.
2. This guiding function must remain after the collision. In general, it can be said that if the first requirement is satisfied, the second one will be also.

The effectiveness of the guiding can be further qualified by the following criteria:

- Roll angle must be kept to a minimum.
- Occupants must not suffer any serious injury.
- The exit angle must be small (to avoid accidents with third parties).
- Specifically for medians and verges between the roadway and the cycle track/footpath: the construction and the vehicle (or parts of them) may not wind up on the other side of the road, putting them in the way of oncoming traffic.

CEN standards

These assessment criteria have been described quantitatively in terms of standards for testing safety barriers (CEN/TC 226, prEN 1317). These CEN tests give a good picture of the degree of safety provided by the tested safety barriers under test conditions. Both flexible steel constructions and rigid concrete constructions appear to satisfy the standards. In this sense, the

tests are valuable for distinguishing good constructions from bad ones and for enabling the comparison of one kind of construction with another.

The CEN tests, however, are based on 'straight' input conditions. Accident under conditions such as slipping, braking, and steering manoeuvres are not involved; it is also hardly possible to realize the many conceivable accidents. Mathematical simulations offer more possibilities in this regard; verification tests must always be a part of these simulations.

Containment levels

The levels of vehicle containment within the CEN-standards are linked with the severity of impact tests that safety barriers should undergo. The assessment of the performance of the barrier is based on criteria of the impact severity and the working width (deflection). If the test is successful, the barrier is ranked within a class of containment level. These levels are divided in low angle containment (T1-T2), normal containment (N1 and N2), higher containment (H1 - H3), and very high containment (H4a and H4b).

The results of investigation by means of the questionnaires give us the information about the qualifications from the European countries of the safety barriers in their own country. Most of the countries qualify their safety barriers in standard situations as 'normal containment level' (N1 -N2) for steel barriers, and as 'higher level' (H1 - H3) for concrete. You wonder how many countries have CEN-test results for these barriers.

The next question is very important: on which type of road had to be installed which type of barrier? Here also the questionnaires give some insight. Asked for were the criteria to place a high performance barrier. The most frequent answers given were:

- danger for lower sited roads, buildings;
- others (bridge parapet, noise protection, water areas, rail crossing);
- narrow median;
- percentage heavy traffic.

Some European countries have made a beginning with these criteria in their standards.

Switzerland's standards regulate the application of level 'H2' (as the highest class) in the case of the protection of hazards with large accident risk. For shielding of railroads and chemical industry plants, a H2-level is also recommended

In Germany a concrete barrier is recommended if the risk for collapse of the barrier is too high. As criterium for a high traffic flow is mentioned 50.000 vehicles in 24 h. Drafts are prepared with characteristics of the following items: accident history, traffic volume, percentage of heavy truck traffic, number and width of lanes, and radius of curves.

Literature study into safety barriers at H4 level

SWOV carried out a literature study on safety barriers at a very high containment level. Tests done in Europe were according to the H4 level of the prEN 1317 standard; it was established that not many full-scale tests at this level had yet been carried out up till now.

In addition, other tests on a similar level as H4 tests are described. These tests were carried out in Japan and the United States and deviate from the H4 tests in that they involve vehicles with a different mass and a somewhat different collision speed and/or collision angle. For inclusion, however, the collision energy was of the same level.

From the research, the following conclusions were drawn:

- Heavy vehicle safety barriers can be made of either steel or concrete. Examples of constructions made of both these materials were found that satisfy the desired H4 level.
- For constructions with small widths, concrete is to be preferred over steel constructions; and for constructions with greater widths, steel is to be preferred.
- The available heavy vehicle safety barriers are higher than current constructions. Vehicle safety barriers with a height of about 1.3 metres appear to provide good results. With a height of about 1.0 metre, vehicle roll-overs (overturning) still occur. Constructions that are 1.3 metres and taller have a positive effect on arresting cargoes.
- The damage suffered from collisions involving a steel construction appears to be much greater than damage suffered from collisions involving concrete safety barriers.
- It appears possible that the ASI (Acceleration Severity Index) values for passenger cars during a collision with a heavy vehicle safety barrier, are below the highest permitted value of 1.4 in the CEN standard.

Experiences with mathematical simulations

Mathematical simulations are very helpful to confirm the effect of construction modifications. Some examples can be shown here.

The first example is a study of the effect of the degree of flexibility of a steel safety barrier on vehicle's decelerations and exit angles. SWOV found that the exit angle at a collision against a flexible construction is an average of 5° smaller than at a collision against a less flexible construction.

The second study of construction modification involved the coefficient of friction of the surface of the concrete New Jersey barrier. Established is the effect of this friction on the climbing height of the vehicle upon collision. It was found that a reduction in the coefficient of friction of 50%, reduces the climbing height up to c. 20 cm, and so the risk of overturning.

During the last years, SWOV also carried out research in the field of movable barriers. With computer simulations, for example, the strength of the connections between the blocks (concrete or steel) and the movement in lateral direction under impact has been calculated.

4.1.3 *New developments*

Steeper profiles of concrete barriers

The fact that the smaller passenger cars have a greater risk for overturning has led a number of European governments (the UK, the Netherlands) to abandon the New Jersey profile and to start using a steeper profile. Although the vehicle's rate of deceleration has somewhat increased, the number of cars expected to overturn is fewer.

Since a steep profile easily leads to damage to the body of the vehicle, the latest development in the Netherlands is the 'Step barrier'. This is a barrier with a steep profile accompanied by a small upright edging at the bottom. Simulations carried out by SWOV show that this edging does not unfavourably affect the course of a collision.

The same results with steeper profiles were established earlier in the United States. Tests with cars with a weight of 815 kg on a vertical-faced concrete wall have shown that such a barrier minimizes vehicle rotation on the longitudinal axis. The vehicle deceleration levels are greater than for concrete barriers with a specially front shape, and the exit trajectories are with a higher arc going away from the barrier.

Need for modifying barriers

Changes in the cross-sections of motorways also makes it necessary to modify safety barriers. Examples of these changes are:

- more traffic lanes for each carriageway which can result in larger crash angles;
- narrow medians that necessitate the use of narrow safety barriers;
- due to increasing traffic concentration, there is a greater need for safety barriers that are maintenance-free and are not seriously damaged during a collision;
- some countries have separate lanes for heavy traffic; a physical separation of truck traffic from other traffic with a barrier is desirable. In these cases there is a need for barriers with different collision properties on either side.
- the increase in heavy truck traffic and buses with a high centre of gravity is necessitating the use of high containment constructions; there are developments in the United Kingdom, Switzerland, Italy, and the USA.

Constructions for single-lane roads

Although construction modifications have the potential for favourably affecting the outcomes of accidents involving safety barriers, vehicular manoeuvres made before the accident, as well as the driver's influence on the path of the vehicle after the collision, are more important. In cooperation with industry, SWOV is now developing a safety barrier for single-lane roads that should allow the vehicle to remain close to the construction and thus avoid the danger of secondary accidents. Initial full-scale tests with a collision speed of 50 km/h produced good results.

The difference between steel and concrete barriers

Based on the experiences with full scale tests and mathematical simulations, the following is concluded for steel and concrete barriers:

- the severity of the accident, in terms of vehicle deceleration, is greater when a concrete barrier is hit;
- when a vehicle hits a concrete barrier with a special profile (no steep profile), the car's front end leaves the ground; especially in the case of smaller passenger cars, there is the risk of overturning;
- the exit angles are larger for concrete barriers.

Based on the investigation results by means of the questionnaires, it can be concluded that road authorities already make a distinction between steel and concrete barriers, based on daily practice. In the questionnaires it was asked for the criteria to place concrete barriers instead of steel ones. The most frequent answers were:

- maintenance of barriers;
- narrow median;
- high volume traffic;
- environment aspects.

Results from European countries

Both steel and concrete barriers have advantages and disadvantages. The *French study* gives the most detailed accident information concerning the difference between steel and concrete barriers. Mentioned is that the severity of accidents against concrete barriers is worse in comparison with accidents against steel barriers. But the amount of rollover accidents as a

result of a collision with a concrete barrier, is relatively high. It is known (from the United States) that accidents with a concrete New Jersey barrier with small vehicles give a high percentage of rollovers. Rollovers are related with serious injuries, particularly if the seat belts were not used.

There are possibilities to prevent this kind of accidents by the choice of a steeper profile instead of a special profile like that of a New Jersey barrier.

It could be possible that if in the French study the number of rollover accidents is estimated as the same for steel and concrete barriers, the difference in accident severity is approximately the same for steel and concrete barriers. An additional analysis with the accident data is recommended.

In *Germany* the choice for steel or concrete barriers for the medians of motorways with a high traffic flow, is based on the prevention of the collapse of the barrier. The risk for an accident with oncoming traffic is too high. Compared to the measures necessary to repair the damaged steel constructions on locations where the accident risk is high, the choice for a concrete barrier gives advantages. As criterium for a high traffic flow, 50,000 vehicles in 24 h. was mentioned. Concrete barriers are recommended if the width of the median is too small for the installation of a steel barrier (< 3 m).

In other situations a case by case decision should be made for the best solution. Aspects to be taken into account are: installation costs, life span, repair costs, load for bridges, risk for an accident, difference in level between both roads, combination with a sound barrier, etc.

In the German article, a table is given with a score for steel and concrete barriers for all these aspects. It concerns here only the medians on motorways with a high traffic flow. According to the total results, the difference between steel and concrete is not large. But for specific locations, sometimes steel is considered for installation and in other situations concrete.

In a German standard, a raised height for barriers is prescribed in the case that there is a danger for overriding: a height of 1.15 m instead of the normal height of 0.81 m.

In *Austria* it is stipulated that concrete barriers are at least equivalent to steel barriers. Mentioned is that concrete barriers give almost a full protection to the collapse of the barrier in cases of accidents with cars and trucks. Experiences have shown that since the application of concrete barriers both the number and severity of the accidents, as well as the extent of material damage has decreased. The reason for the decrease of the severity is due to the reduction of accidents related to the collapse of barriers. Regarding the rebound at a collision, experiences with concrete barriers are more favourable than expected.

Also in *the Netherlands*, steel barriers were compared with concrete barriers. Aspects taken into account were: installation costs, costs of maintenance, and number and severity of accidents. The data of accidents were gathered from other countries owing to the little use of concrete barriers in favour of steel ones.

The conclusion is that steel barriers in principle can be preferred. The total costs considered are higher for concrete barriers in comparison with steel barriers. Concrete barriers are recommended in situations with medians with a small space.

4.1.4 *Proposals for standards and strategies for EU countries*

Motorways: shoulders

There are safety reasons for favouring wide obstacle-free zones. 6 of the 13 countries that provided information maintain a minimum width of 9 m. This width is recommended as a provisional minimum. This distance is not chosen in advance as an absolutely safe width. But by gradually widening the width of the obstacle-free zone, the road authority will be more easily tempted to choose a safety barrier than a safer obstacle-free zone. Recommended is to carry out accident investigations in different European countries to collect more data in order to take a more well-founded decision for the European situation.

Slopes may be a part of an obstacle-free zone if vehicular manoeuvres are possible. This is the case with a gradient of at least 5:1 for high slopes (> 5m) and 6:1 for lower slopes (< 2m). Only fixed roadside objects can be located within an obstacle free zone, if their support poles are flexible. If solitary rigid obstacles cannot be relocated, protecting them with a crash cushion is the solution.

A decision model is described by Schoon (1998) for determining the choice: obstacle free or safety barrier.

Motorways: medians

In terms of safety, an obstacle free-zone for off-the road vehicles in the median had to be at least 20 m. Normally this width is out of the question. As a result, a choice has to be made for the type of safety barriers. In this case the question is: what should be the containment level of the safety barrier? The level depends on the circumstances of the cross-section, the traffic volume, proportion of heavy traffic, and so on. Some European countries have made a beginning with criteria in their standards about containment level. Drafts are being prepared. The question 'steel or concrete barrier' had to be answered in relation to the choice for a high or low containment level. Besides the aspect of sufficient resistance, the aspect of enough height to prevent rollover to the other carriageway is also important.

If a decision is made for a low containment level, steel barriers are in favour if only the installation costs are calculated. Taking into account other aspects, it depends on the local circumstances which type of barrier is to be preferred. Differences between countries are too great for a general statement here.

Express roads: dual carriageways

If express roads have dual carriageways, it is necessary for road safety that a safety barrier be built in the median. As far as the requirements for the safety barriers are concerned, there is not much difference between those for safety barriers on motorways. The containment level is probably lower because of the lower design speeds of the road.

Obstacle-free zones are preferred for the shoulders. For the width of these zones, Schoon (1998) indicates that they should be about 6 m. Six of the thirteen countries who answered the SAFESTAR questionnaire use this (or a greater) width. If there is not enough space in the shoulders, safety barriers can be placed.

Express roads: single carriageways

It is to be preferred that the roads of this type with a high traffic volume have some kind of physical separation of carriageways on the road axis. This is in agreement with the (modern) ideas of separating two traffic flows in opposite directions (sustainable safety).

The shoulders are obstacle-free with a width of at least 6 m (see above). Safety barriers such as those used on motorways do not fit this type of road because there is the danger of reflections, and therefore the chance of a frontal accident with traffic on the other lane. Special constructions are needed for this which will keep hold of a car during a collision. At this moment a construction is being developed in the Netherlands.

If there are high-risk zones (viaducts, watercourses, ravines), standard safety barriers must be placed.

4.1.5 *Strategies for attention to obstacle accidents*

Renewed attention in the US

It is striking that experts in America observe that, for decennia already, attention has been paid to the problem of obstacle accidents. This problem, however, is getting bigger and bigger. Furthermore, they maintain that studies carried out in the 1970s have lost their validity many years ago, partly as a result of changing cars.

The problems being signalled are mainly those of highways. The strategy developed in America to deal with these problems appear to be applicable in Europe:

- better accident monitoring;
- research on the interaction of aspects from roads, vehicles, and drivers;
- give the problem fresh attention by education, spreading information, good management, planning;
- greater budgets; working at fund-raising;
- traffic laws.

Increase of obstacle problems in Europe

The single carriageway roads are in fact at the heart of the problem of obstacle accidents in Europe. There are so many such accidents because there are so many old roads. Unfortunately, such accidents are widely spread so that dealing with them cannot be targeted at concentrations of dangerous locations.

The relative number of such accidents is also on the increase: the percentage of fatal off-the-road accidents, in comparison with the total number of accidents was 13% in 1971, and in 1996 this was 26 %; a doubling during a period of 25 years. This increase applies to the Netherlands, but probably also applies to other European countries.

Identification and approach

Schoon (1998) has described a procedure for identifying the locations and establishing priorities for those most requiring the placing of safety barriers. Seven steps are distinguished; one of which is carrying out observations of locations and a cost-benefit analysis. Owing to the application of a cost-benefit analysis, within this method also the 'one million ECU test' of the European Commission can be applied.

Where (isolated) fixed objects are standing in the shoulder, there are solutions for making poles etc. frangible.

The 'natural' obstacles such as trees present a greater problem because cutting them down is prohibited and/or because of landscape preservation. Apart from the erection of safety barriers, to increase the safety of such roads, the speeds driven will have to be drastically reduced. Subsequently this means that the road's function will be changed; from that of a through-road to one with a more local character.

Computer simulations

Computer simulations techniques can be used to augment the traditional crash testing programme, with as advantages, reducing the costs and improving the range of test condition when developing or redesigning roadside hardware. At this moment the CEN standards offer no possibilities to use mathematical simulations as an instrument to support full scale results. Recommended is to discuss this item within the CEN consultations.

5. TUNNELS

5.1 Introduction

Road tunnels have been applied to cross natural obstacles, like mountains, rivers, canals and major navigable waterways. More recently, tunnels are applied in dense populated areas. In these areas the availability of land for surface routes is decreasing, while on the other hand there is a growing demand for mobility. Another development favouring the tunnel option has been the increased demand for environmental protection from traffic. This includes the aesthetical value of the landscape, noises and pollution produced by large traffic streams.

The tendency is to build more complicated infrastructure with high capacity under ground. Several European countries are working on long stretches of motorways in tunnels in the near future. This can be illustrated by the following two examples.

- 1 The Swedish 'Ringprojekttet'. an underground motorway network to replace the motorways around Stockholm.
- 2 An initiative in the Netherlands, where because of new residential areas the motorway west of Utrecht will be built underground.

Due to technical and financial constraints, the design of tunnels on motorways is often different from the design of standard motorways. An example of a financial constraint is the application of an emergency stopping lane. The aim of an emergency stopping lane is as follows (PIARC, Technical Tunnel Committee, 1987):

- I Improving safety
- II Allowing vehicles to stop and allowing for breakdowns
- III Allowing emergency services access to accidents on busy routes
- IV Allowing accidents to be bypassed
- V Allowing generous facilities during maintenance
- VI Maintaining good level of service.

Furthermore the Technical committee Road Tunnels of PIARC wrote in their contribution to the XVIII th World Road Congress (PIARC, 1987, p.126): "In tunnels, where the cost is extremely high for every metre extra width, care has to be taken that only economical cross sections are used in designs. Thus the question of width of tunnel emergency stopping strips or lanes has to be considered in detail."

The problem is how one determines a solution to be economical. For a particular tunnel the extra cost for building an emergency lane can be calculated. On the other hand it is difficult to calculate the revenues, particularly when safety is concerned. In the first place it is hard to estimate the number of saved victims, secondly valuation of the saved victims is even more complicated.

The objective of work package two of SAFESTAR has been special dedicated to the support of design standards for tunnels on motorways. To guarantee safety in tunnels, it is necessary to assess to what extent it is acceptable or even required to deviate from standard motorway

design criteria. Furthermore, additional criteria are needed for matters affecting safety, which only apply to road tunnels like wall pattern and tunnel height. The study has been divided into three parts: a literature review (Martens & Kaptein, 1998a), a survey of tunnel design guidelines (Martens & Kaptein, 1998b) and a validation of three design features in a simulator (Martens, Törnros and Kaptein, 1998). The two partners participating in this work package were VTI from Sweden and TNO Human Factors Research Institute from the Netherlands.

The setup of this chapter is as follows. In the next paragraph the unsafety of motorway tunnels is compared with the open situation. Only very rough data, retrieved from literature, is used. Additional data collection was beyond the scope of this project. The subsequent paragraph deals with the relationship between traffic safety and alignment and cross section. Clearly, traffic safety is not the only factor which determines the alignment and the cross section of a tunnel. Alignment and cross section are also the result of technical considerations like:

- the ground conditions (rock, soft ground);
- construction method (drill and blast, cut and cover, tunnel boring machine);
- available area;
- the existing road network.

In paragraph 5.4 entries and exits within a tunnel are discussed. In paragraph 5.5 some remarks are made concerning lighting in tunnels. The last paragraph of this chapter contains the conclusions and recommendations concerning future research.

Beside the subjects mentioned in the previous sections, there are several other objects in tunnel design concerning safety which are not treated here. Tunnels, particular on motorways, are equipped with all sorts of additional equipment regarding safety. Systems like emergency telephones, emergency exits, fire detection, water hoses, fire extinguishers, Closed Circuit Television (CCTV), Variable Message Signs (VMS), ventilation and drainage system have in common that there is no direct influence on the behaviour of drivers. These systems are necessary to keep the tunnel accessible to the public and are used once an accident has happened. An exception is CCTV. The tunnel operator can use information collected with CCTV to close a lane, or change the mandatory speed limit in the tunnel.

5.2 Tunnel safety compared to open road conditions

In the same publication cited above the PIARC Tunnel Committee suggests that a comparison of the tunnel situation with a similar setup in the open is useful, especially as much more data are available on the use of the open road. One way to compare tunnels is to study accident rates. At several World Road congresses, The PIARC Tunnel Committee has published breakdown and accident statistics of tunnels. From the statistical point of view there are several problems with these figures. For example, several countries have their own definition of a fatal accident. In the Netherlands an accident is recorded to be fatal when a victim dies within 30 days after the accident, in Belgium the victim should have died on arrival in the hospital. In the following table the number of accidents with injured people per 10⁸ vehicle kilometres in a number of tunnels on motorways is compared with the same figure for motorways in the open for the country where the tunnel is situated. The tunnel data have been extracted from the PIARC publication "Road Safety in Tunnels" (PIARC 1995). The tunnels presented in table 1, are unidirectional tunnels, with a minimal length of 1 km, and known injury accidents rate. The data

of the open motorways have been extracted from the IRTAD database. The presented rate for open roads has been calculated as the mean value of the rates of the same years studied by PIARC. In the case that IRTAD did not contain information over a similar time period as presented by PIARC, a rate has been calculated over a time period as close as possible.

| tunnel | country | length [km] | lanes tub.x lan. | gradient % | injury accidents/10 ⁸ veh.km | |
|--------------------|---------|-------------|------------------|-------------------|---|--------------|
| | | | | | tunnel (studied period) | open roads |
| Oslo Tunnel | Norway | 1,8 | 2 x 3 | 4 - 7 V shaped | 7 (90-93) | - |
| Floyfell | Norway | 3,9 | 2 x 3 | 1 | 5 (88-91) | - |
| Brooklyn Battery | USA | 3,2 | 2 x 2 | - | 50 (89-91) | 23 (89 - 90) |
| Queens Midtown | USA | 2,8 | 2 x2 | - | 81 (89-91) | 23 (89 - 90) |
| Holland | USA | 2,6 | 2 x 2 | V shaped | 33 (87-91) a) | 23 (89 - 90) |
| Lincoln | USA | 2,5 | 3 x 2 | V shaped | 26 (87-91) | 23 (89 - 90) |
| Elbe | Germany | 2,7 | 3 x 2 | V shaped | 30 (87-91) | 18 (90) |
| Söder | Sweden | 1,1 | 2 x 2 | - | 4 (87-91) | 11 (93) |
| Ville-Marie b) | Canada | 2,8 | 2 x 3 | 2 - 3 | 8 (88-91) | - |
| L. Hyp. Lafontaine | Canada | 1,4 | 2 x 3 | 4 - 5 | 29 (87-91) | - |
| Kaiser Mühlen | Austria | 1 | 2 x 2 | - | 0 (89-91) | 18 (89-91) |
| Limfjord | Denmark | 1,1 | 2 x 3 | - | 17 (87-91) | 4,4 (87-91) |
| Dullin | France | 1,5 | 2 x 2 | 2,4 | 4 (84-91) c) | 10 (85-91) |

a) multiple accident

b) with 9 entrance ramps and 9 exits ramps

c) only one event was recorded

Table 5.1 *Characteristics of different tunnels and their safety record*

From the data in table 5.1 one cannot conclude that the safety is better in the open than in tunnels nor that safety is better in tunnels than on open roads. The PIARC Tunnel committee state however (PIARC, 1995) that road safety in tunnels is better than on open roads, except in case of failure in the geometric design. In literature (PIARC, 1983) high accident rates in existing tunnels are associated with steep gradients and sharp curves.

The level of unsafety differs for each tunnel. The used sources provide not sufficiently data to analyse the cause of these differences. For example, detailed data like the presence of an emergency lane.

5.3 Alignment and cross section

The design guidelines of the alignment and the cross section of motorways, are partly based on research, partly on experience. European countries have developed design guidelines more or less independently from each other, hence the design guidelines for motorways differ between EEC member countries. So, when we discuss the substandard design of motorway tunnels in Europe, there is also a wide variance between the tunnel design guidelines used in Europe. In deliverable 2.2 of SAFESTAR (Martens & Kaptein, 1998b) the motorway guidelines of Sweden and the Netherlands are used as reference for the research work.

An important criterion for the design of alignment and cross section for motorways in both the open as in tunnels is sight distance. Sight distance is an objective criterion which can be calculated from the dimensions of the road section. Because of ceiling and walls, sight distances in tunnels are limited in comparison to the open road situation. Clearly, parameters like width, height, sight distance, applied radius in curves and gradients contribute to direct the tunnel user to behave as desired. However even more important is how the tunnel user perceives the tunnel environment. The perception of the tunnel user can be influenced by applying certain wall patterns, particular road markings and signing.

A limited sight distance in motorway tunnels can partly be compensated by supplying the driver with information concerning the current traffic situation in the tunnel. This information can be given by means of VMS, green arrow/ red cross panels. The tunnel operator can use information obtained from CCTV and traffic flow measurements to decide on the contents of the messages to the drivers.

Special attention should be paid to road sections in the vicinity of the tunnel portals. In these sections the transition takes place from open road conditions to tunnel conditions and vice versa. On road sections close to the tunnel portals, relatively more accidents happen than in the tunnel itself (Admundsen, 1994). One major problem in the transition area is lighting (See paragraph 5.4). Furthermore, particular in the case of long tunnels, the cross section will change. The road sections just outside the tunnel portals should be used to prepare the driver for the changes he will face. Research indicates that (Martens & Kaptein, 1998a), drivers pay extra attention to the tunnel entrance. It should therefore be avoided to erect signs over a length of 150-200 m in front of the tunnel

5.3.1 Alignment

In this section tunnel length, curves and gradients, will be discussed. A number of authors referenced by Martens & Kaptein (1998a) found by means of questionnaires that people experience more fear with increased tunnel length. There are however no clues presented from accident statistics that a longer exposure to fear leads to more accidents.

Small curves should be avoided, especially if they are connected to a straight alignment. The PIARC Tunnel Committee recommend observing a minimal curvature of 550-600 m. (PIARC, 1995). It is not clear if this figure applies for all tunnel types. Still, a radius of 550m is substantial less than the minimum requirement of 750 m in the Dutch motorway guidelines. A

radius of 750 m may only be applied in case where room is limited. Under normal conditions a radius of 2000 m. should be observed.

In case of a tunnel however there can be several other boundary conditions which force designers to apply a smaller radius than one should do from road safety point of view. In the case of a curve in a motorway in the open, the designer has several tools to inform the driver about the curve he approaches. In tunnels it is more difficult for the driver to detect curves, to predict the radius and therefore to choose the appropriate speed. A method to inform the driver for an upcoming curve is to use a certain wall pattern. In work package 2.3 (Martens, Törnros and Kaptein, 1998), a simulator study with the VTI driving simulator has been performed, to investigate if certain wall patterns on the last 200 m of the straight section before the curve influence the speed behaviour of drivers. Seven different patterns, including no pattern, and a similar road stretch in the open have been studied. Subject had to drive all stretches four times, of which half without speedometer readings. Driver behaviour was studied by analysing average speed, average lateral position, and lateral position variability. Additionally, position of gas pedal release, position of deceleration initiation, position of maximal deceleration, and maximal deceleration have been analysed. No influence of the simulated wall patterns was found however on speed behaviour. However, the results of the questionnaire show that a majority of the subjects indicate that the patterns had speed reducing effect. For three of the patterned conditions, a small difference occurred of lateral position compared to the open road condition.

Another important aspect of alignment is the gradient of the road. As in the open situation, also in tunnels gradients influence both the capacity and road safety. Main cause is the speed difference between cars and heavy trucks leading to inhomogeneous traffic. Because of the high costs, steeper gradients are accepted in tunnels than for motorways in the open. More research is needed to determine what gradient is acceptable concerning capacity and road safety for tunnels on motorways.

5.3.2 *Cross section*

The overall shape of the cross section is determined by the construction method. A circular cross section is the result of the use of a tunnel boring machines. The traditional horseshoe-shaped tunnel is typical for drill and blast, a square cross section one will find in cut and cover tunnels.

As mentioned earlier in this chapter, a tunnel designer will whenever possible minimise the area of the cross section, because of the high costs. The effect of the smaller cross section is that there is no room for an emergency lane. A number of studies have been performed to examine the effect on behaviour when a driver drives from a motorway section with an emergency lane to a tunnel section without an emergency lane. The results of these studies show that a decrease of the lateral width affects speed behaviour and the lateral vehicle position.

In the TNO simulator study (Martens, Törnros and Kaptein, 1998) performed in the framework of this study, driver behaviour was studied of subjects driving over the transition from a wide cross section into a smaller cross section. The wide cross section was according the guideline of Dutch motorways. Four small cross sections were included into the study design, with

different emergency lane widths, varying from 5,75 m (emergency lane 3.50 m + 2.25 m lateral clearance) to only a lateral clearance of 0.5 m. . These four transitions were simulated in an open road condition (control) and a tunnel condition (experimental) each for two traffic flow conditions. Driving behaviour has been expressed in terms of speed and the distance between the right road marker and the right side of the car. The experiment shows that lateral width per se influences driving behaviour and that this effect is stronger in a tunnel. However, the effects on lateral position and speed are relatively small. The authors (Martens, Törnros and Kaptein, 1998) recommend not to omit an entire emergency lane in tunnels. If for some reason it is impossible to include an entire emergency lane in the design, an emergency lane of 1.50 is expected to reduce the negative effects on road capacity and traffic safety.

5.4 Entries and Exits

In the near future the number of tunnels containing entries and exits will increase. In work package 2.3 (Martens, Törnros and Kaptein, 1998), the results were presented of an investigation into the effect of sight distance, presence of an emergency lane and traffic flow on driving behaviour on motorway entries and exits in tunnels. The study was performed with the TNO driving simulator. Driving behaviour was measured by means of the driving speed, accepted gap, Time-To-Accident and the amount of space subjects use to perform the manoeuvre. For the investigated sight distances (84m-300m) no effect was found on driving behaviour. Furthermore, no differences were found between merging/exiting in open road conditions and in tunnel conditions. All subjects managed to perform the manoeuvres in a relatively safe manner, also in the absence of an emergency lane. However, the results of the questionnaire indicate that an emergency lane is required in case of entries in a tunnel.

5.5 Lighting

Tunnel lighting is an important issue, and there has been published quite a lot on this subject. This however has not resulted in one internationally accepted method to calculate lighting levels in the transition area and within tunnels itself. Maybe a comparison should be made between the methods by evaluating the road safety in tunnels where different calculation methods have been applied.

5.6 Conclusions and recommendations

In the ideal situation, a tunnel in a motorway should not have effect on the level of service and road safety. In reality however this is not the case. For the motorway in the open detailed design guidelines are developed, where tunnel designs depend largely on the local situation

Hence there is a need to quantify the effect of tunnel design parameters on traffic safety. Ideally, the tunnel designer should have a quantified relationship between a particular design feature and road safety at his disposal to judge if a certain tunnel design is acceptable in terms of road safety.

Simulator studies give only a comparison between how drivers behave in tunnels and motorways in the open under certain conditions. Driver behaviour in this case is described by speed, lateral position of the vehicle and steering frequencies. There is not a direct relationship

between these parameters and traffic safety, i.e. registered number of accidents. Clearly, simulation is a very powerful tool to study new tunnel designs, but more attention should be paid to the relationship with the real world. A research setup would be to simulate an existing tunnel with known accident statistics. By this way a relationship can be found between measured human behaviour and (certain types of) accidents.

Beside simulation, more structural and detailed data collection, concerning driver behaviour and accidents should be performed in existing motorway tunnels. The problem is that one needs long collection periods, at least five years (PIARC, 1995) to obtain significant results from the collected data. During such periods there should be not too many changes in the tunnel.

In the simulator study (Martens, Törnros and Kaptein, 1998) the effect of a number of wall patterns was examined on the speed behaviour of drivers. The idea was to reduce speed before the beginning of a curve. However no effect was found on speed behaviour, the basic concept is very interesting. If for some reason the tunnel design deviates from the motorway standard, one could look for compensation by means of using the additional equipment, which is available in tunnels but not on motorways. For example, the tunnel operator using CCTV can close a lane when a vehicle has stranded. This can compensate for the absence of an emergency lane.

6. JUNCTIONS AND INTERCHANGES

6.1 Express roads

Though junctions and interchanges constitute a very small part of the express road network, a substantial part of the accidents happen here. Analysis of accidents on express roads in Portugal (Cardoso & Costa, 1998) showed that on dual carriageway express roads 11 per cent of the accidents were located at junctions; on single carriageway express roads 20 per cent of the accidents were located at junctions. The majority of junction accidents both at dual carriageway and single carriageway express roads are lateral accidents, and as such the express roads are comparable to ordinary roads (see Table 6.1), where the most important junction accident type is also a lateral accident. At dual carriageway express roads lateral accident are relatively less frequent than at single carriageway express roads.

| | Accident | | | | HIT PEDESTRIANS | RUN OFF THE ROAD | TOTAL |
|-------------------|----------|----------|---------|----------|-----------------|------------------|-------|
| | Frontal | Rear end | Lateral | Obstacle | | | |
| 2x2 Motorway | 5 | 23 | 16 | 17 | 4 | 31 | 96 |
| 2x2 Express road | 19 | 12 | 32 | 11 | 5 | 18 | 97 |
| 2x2 Ordinary road | 7 | 8 | 56 | 3 | 16 | 7 | 97 |
| 2x1 Express road | 16 | 12 | 49 | 7 | 6 | 7 | 97 |
| 2x1 Ordinary road | 24 | 11 | 46 | 5 | 8 | 5 | 99 |

Table 6.1 *Accidents at junctions at different road classes by accident type (in percentages).*

Given the high accident risk at junctions, in combination with the function of express roads (long distance travel) the number of interchanges should be limited. Both single and dual carriageway express roads can have grade-separated or at-grade junctions, although grade-separated is more common at dual carriageway express roads. In general, grade-separated junctions are safer than at-grade junctions (Ogden, 1996). For example, Hedman (1990, cited by Ogden, 1996) found that in Sweden, grade separations resulted in 50 per cent accident reduction at a cross junction and 10 per cent reduction at a T-junction. Whereas it is often heard that grade separated junctions at non-motorway roads may confuse road users, resulting in motorway driving behaviour, no empirical proof has been found that this actually happens or adversely affects safety. It is believed that the safety gains of grade-separated junctions outweigh the safety losses caused by possible confusion. It is very important, though, that either type is used consistently along a particular road in order not to violate drivers' expectations and hence induce inappropriate behaviour.

In a UK study on class A roads, which are very similar to express roads although they are open to non-motorised traffic, it was found that the following aspects of grade separated junctions were associated with accident frequency (Hughes, Amis and Walford, 1996):

Grade separated junctions, on-ramps

1. Minor road traffic flow: a 1,000 vehicle increase in the number of vehicles entering the main road from the minor road results in a 16 % increase in accidents.
2. Vertical alignment of on-ramp: compared to an on-ramp arrangement where the vertical alignment is level, on-ramps with positive vertical alignment and negative vertical alignment are associated with increases in accident frequency of 350 % and 250 % respectively. On-ramps with a sag or crest profile are associated with 500 % more accidents than those with level alignment.
3. Distance to next junction: as the distance to the next junction increases, accident frequency at the preceding junction decreases. A one kilometre increase in inter-junction distance results in a 26 % decrease in accident frequency.
4. Verge width on offside of on-ramp: the presence of a wide verge on the offside of the on-ramp results in a 90 % reduction in accident frequency (compared to a narrow verge).
5. On-ramp merging length: accident frequency decreases as the length of the merging lane between the end nosing and the end of the on-ramp increases. A 100 m. increase in merging length results in a 6 % decrease in accident frequency.

Grade separated junctions, off-ramps

1. Exit traffic low: a 1,000 vehicle increase in the number of vehicles leaving the main road onto the minor road results in a 13 % increase in accidents.
2. Vertical alignment of off-ramp: compared to an off-ramp arrangement where the vertical alignment is level or negative, off-ramps with positive or crest vertical alignments are associated with an increase of 124 % in accident frequency.
3. Distance to next junction: as the distance to the next junction increases, accident frequency at the preceding junction decreases. A one kilometre increase in inter-junction distance results in a 61 % decrease in accident frequency at the off-ramp.
4. Verge width on offside of off-ramp: the presence of a wide verge on the offside of the off-ramp results in a 79 % reduction in accident frequency (compared to a narrow verge).

Since the number of grade-separated junctions incorporated in this study was relatively small, the actual numbers should be used with care. However, it becomes clear that, in order to optimise safety of grade-separated junctions, on-ramps and off-ramps should be level and should have wide verges. Merging lanes need to be sufficiently long and junctions should not be located too close to each other.

With respect to at-grade T-junctions at single and dual carriageway 'A' class roads (Hughes and Amis, 1996; Hughes, Amis and Walford, 1996) the following aspects were found to be related to accident frequency:

T-junctions, single carriageway roads

1. Major road traffic flow: within the major traffic flow range considered in the model (4,500 to 17,400 vehicles per 16 hour day), an increase of 1,000 vehicles per day results in a 6 % increase in accidents.
2. Minor traffic flow: an increase in minor traffic flow from one categorical level to the next results in an increase in accident frequency of 87 %. (levels: 0-1,000 veh., 1,000-2,500 veh., 2,500-4,000 veh., and 4,000-5,000 veh. per 16 hour day).

3. Carriageway width: within the carriageway width range considered in the model (7.0 m. to 21.2 m.), a one metre increase in carriageway width at the junction results in an estimated accident reduction of 5 %.

T-junctions, dual carriageway roads:

1. Minor road traffic flow: an increase of 1,000 vehicles per 16 hour average annual weekday flow entering the dual carriageways from the minor road results in an increase of 120 % in accidents at the junction.
2. Gap in central reservation: T-junctions served by a gap in the central reservation are associated with 270 % more accidents than T-junctions having no gap. The larger amount of accidents in this situation is explained by the presence of left turning vehicles from the side road to the express road (right turning in the British situation). This relatively high-risk traffic stream is excluded in the situation where there is no gap in the central reservation.
3. Traffic using gap in central reservation: a 10 % increase in the proportion of minor road traffic flow using a gap in the central reservation results in a 9 % increase in accidents at the junction.

With respect to single carriageway at-grade junctions it is difficult to come to specific design recommendations. For dual carriage-way T-junctions it is clear that a central reserve allowing for left turns (right turns in the UK) substantially increases the accident frequency.

Roundabouts are a very safe way of junction design since they reduce both the accident speed and the impact angle (Slop et al., 1996). However, given the high speed requirement of express roads, they are less suitable for this type of roads. Nevertheless, as is the case in France, roundabouts could be used at the beginning and the end of an express road coming from or entering an ordinary road. This may be useful since it clearly marks the transition from one type of road to another. In case of leaving the express road it may also contribute to breaking the high speed habituation process and the resulting underestimation of the own speed, which has been shown to appear when people have driven at high speeds during a longer time period (ETSC, 1995).

6.2 Design of major urban junctions

SAFESTAR deals with the roads in the TERN, and this road network is situated outside urban areas. From the TERN report it can be understood that urban sections will virtually not be part of this network in the long term. Nevertheless, in the additional information received, urban conditions are referred to several times. In view of this, it has been assumed that urban sections will occur on TERN links at least for some more considerable time, presumably as main thoroughfares. Therefore, a limited amount of attention is paid to urban conditions. This attention has been concentrated on major urban junctions.

6.2.1 Design principles

The design philosophy in Chapter 1 defines three design principles, which should also be applied to the design of (major) urban junctions:

- A functionally planned road network: each link fits well into the whole system and actual route choice is in accordance with planned route choice.
- A homogeneous use of the road: road users should only be confronted with small differences in speed and mass.
- A recognizable road environment which stimulates the right expectations: predictability of traffic situations.

Elaborating these principles when classifying the road network has an important drawback for the selection of the type of junctions:

- Each road class should have a limited number of different types of junctions
- A road class should only be connected to another road class according to table 6.2:

| | Interconnective road | Distributor | Access road |
|----------------------|----------------------|--|--|
| Interconnective road | grade separated | grade separated | n.a. |
| Distributor | grade separated | at-grade, priority regulation, speed reduction | at-grade, priority regulation, speed reduction |
| Access road | n.a. | at-grade, priority regulation, speed reduction | at-grade, no specific priority regulation, speed reduction |

Source: CROW (1997)

Table 6.2 *Operational requirements for connecting road classes (by a certain type of junction)*

Type of junction

Speed reduction near and at the junction plays an important role in meeting the second design principle. Speed reduction can be attained by physical measures (including the application of roundabouts), and partly by signalization (e.g. by signal coordination at successive junctions). See Table 6.3 for the type of junction which is recommended for each possible connection of the different road classes. The connection of two interconnective roads will mostly not be situated in the urban area, while the connection of two access roads will not be part of the TERN network

Generally four-arm junctions are not recommended for priority junctions: the number of injury accidents at four arm junctions is relatively high; see Figure 6.1. Roundabouts are superior to both three- and four-arm junctions with respect to the number of injury accidents (VTI, 1998; Van Minnen, 1990; Stuwe, 1991).

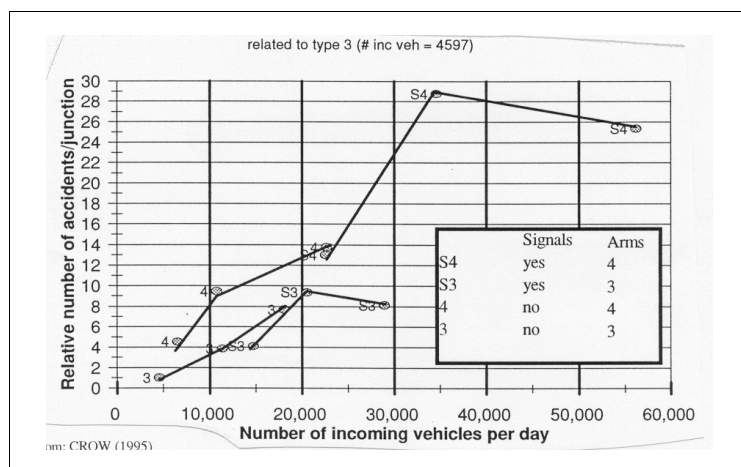
VTI (1998) has found the 'best choice' regarding type of junction for different combinations of entering flows on the major road and the minor road (see Section 6.2.2).

An important, but not surprising, finding in many accident evaluations is that the flow level is the most dominant predictor of the number of (injury) accidents at junctions.

| | | | |
|----------------------|--------------------------|---|---|
| | Interconnective road | Distributor | Access road |
| Interconnective road | interchange | grade separated junction | n.a. |
| Distributor | grade separated junction | roundabout, signalized junction | roundabout, three-arm signalized or priority junction |
| Access road | n.a. | roundabout, three-arm signalized or priority junction | three-arm junction |

Source: CROW (1997)

Table 6.3 *Types of junctions according to requirements in Table 6.2*



Source: CROW (1995)

Figure 6.1 *Relative number of accidents at four types of urban junctions*

Predictability of traffic situations

The predictability is a combination of expectation (what could happen), and observation (what can be seen).

The observation can be improved by making the road environment less complex, e.g. by removing obstacles which prevent a good sight, and by separating different types of conflicts (in time or space).

The expectation is for a great part a matter of education and training. The road environment can support and ease this training by offering layouts which are as uniform as possible. Furthermore the road environment should trigger the right expectations: First of all, the approach of a junction must be stressed. Second, the possible types of encounters must be clear from the marking, signing and other clues before entering the junction. Finally, the layout of the junction must be logical and adapted to the skills of the road user, preferably the less vital road user.

Safety effects of design features

The urban area shows an enormous variety in design elements, in layout of these elements, and in traffic situations. Evaluating the safety effects of different types of elements or layout

configurations, both in different traffic situations, is a huge operation. This can only be done by using the best research methodologies, by gathering large amounts of data, and by applying sophisticated statistical techniques. A good example of such an approach is given by Elvik et al. (1997). It will take many years to evaluate the large number of possible design elements and layout configurations, assuming that this job will start one day.

For the time being, knowledge about the safety effects of design features is spread over many reports and institutes. Part of this knowledge is filtered through in SAFESTAR (Danish Road Directorate, 1998).

Priority junctions

The relationship between the gap acceptance by motorists and the number of accidents has not been established yet. However, this relationship can indirectly be found by using accident models which account for both the flow on the major road and the minor road. These models will be treated separately in this chapter (Section 6.2.2).

| FALLGRUPPE 1 | FALLGRUPPE 2 | FALLGRUPPE 3 | FALLGRUPPE 4 | FALLGRUPPE 5 |
|--|--|---|--|---|
| MARKIERUNG DER FURT AN EINMÜNDUNGEN OHNE LICHTSIGNALANLAGE | ABSETZUNG DER RAD-VERKEHRSANLAGE AN EINMÜND. OHNE LICHTSIGN. | ABSETZUNG DER FURT AN KNOTENPUNKTEN MIT LICHTSIGNALANLAGE | FÜHRUNG DES GERADE-AUSVERKEHRS AN FREIEN RECHTSABBIEGEFAHRBAHN | FÜHRUNG DES RADVERKEHRS AN KREISVERKEHRSANLAGEN |
| | | | | |
| KEINE MARKIERUNG | FAHRBAHN | FAHRBAHN | FAHRBAHN | FAHRBAHN |
| | | | | |
| EINFACHE MARKIERUNG (SCHMALSTRICH) | RADFABHREIFEN | RADFABHREIFEN | RADFABHREIFEN | FAHRBAHN |
| | | | | |
| DEUTLICHE MARKIERUNG (BLOCKM., BREITSTRICH, EINFÄRBUNG) | RADWEG, GERING ABGESETZT | RADWEG, GERING ABGESETZT | RADFABHREIFEN | UMLAUFENDER RADFAHREIFEN |
| | $a = 2-4m$ | $a = 2-4m$ | | |
| TEILAUFPFLASTERUNG | RADWEG, MITTLERE ABSETZUNG | RADWEG, MITTLERE ABSETZUNG | RADWEG, GERING ABGESETZT | UMLAUFENDER RADWEG |
| | $a > 4m$ | $a > 4m$ | | |
| | RADWEG, WEIT ABGESETZT | RADWEG, WEIT ABGESETZT | RADWEG, WEIT ABGESETZT | |
| | | | | |

Source: BASt (1992)

Source: BASt (1992)

Table 6.4 Different types of facilities for cyclists at different types of junctions

Facilities for cyclists

Facilities for cyclists have a great variety in design and layout. Some of these facilities have been evaluated thoroughly. BASt (1992) gives an overview of the most common facilities at junctions; see Table 6.4.

Facility types 20 and 21 ('no facility' and 'cycle lane') had the lowest accidents rates per junction (also when taking the number of passing cyclists into account) compared to facility types 22, 23 and 24 ('separated cycle path') (BASt, 1992).

The Danish Road Directorate (1994) has evaluated some new types of facilities for cyclists. The main goal of these new types is to let cyclists and motorists be aware of a possible encounter or conflict. So the facilities stress the position on the carriageway where cyclists are supposed to ride. The effect of these facilities on road safety appeared to be satisfactory.

Roundabouts

The number of (injury) accidents as a function of the entering flow, can be calculated with an accident model. This item is treated separately in this chapter (Section 6.2.2).

Three different types of facilities for cyclists (defined by BASt, 1992) have been compared with each other (Table 6.4). For two indicators, the number of injury accidents per junction and the number of injury accidents per million bicycle kilometres, it appeared that type 50 ('no cycle facilities' at the roundabout) had the lowest accident rates, and that type 52 ('cycle path') had the highest accident rates (BASt, 1992). This result has also been found by Van Minnen (1998). However, Van Minnen (1998) also evaluated a facility which had even lower accident rates than type 50: a roundabout with a cyclepath (like type 52) but with the restriction for cyclists that they have no right-of-way at the crossings.

Signalized junctions

As for the other types of junctions, the number of accidents related to traffic flows (motor vehicles, cyclists, and pedestrians) is treated in Section 6.2.2.

Typical safety problems at these type of junctions are red-light running and rear-end accidents. Red-light running, especially by cyclists, may be caused by too long delays. Rear-end accidents have to do with the predictability of the traffic situations: If the driver is aware of the junction and the presence of signalization, then the driver will be prepared for vehicles stopping in front of him/her.

Regarding facilities for cyclists (Table 6.4), BASt (1992) has found that facilities 30 ('no facility') and 31 ('cycle lane') have lower accident rates than facilities 32, 33 and 34 ('cycle path').

6.2.2 Quantitative relationships between accidents and traffic flows

Several countries are developing models for accidents on junctions. The United Kingdom has a long tradition in this respect. Tanner reported already in 1953 about models for accidents on rural T junctions (Jadaan & Nicholson, 1992).

Nowadays countries like Sweden, Finland and Denmark have much experience in fitting accident models for junctions. Literature shows a slight preference for models regarding urban junctions. At least SAFESTAR concentrated on major urban junctions, as part of roads in the TERN network.

Accident models which give a description of accidents on junctions mostly have the following structure:

$$A = c * Q_1^a * Q_2^b \quad (20)$$

- A: number of accidents
- c: estimated parameter
- Q₁: number of entering vehicles per day on the major road
- Q₂: number of entering vehicles per day on the minor road
- a: estimated parameter
- b: estimated parameter

The Swedish model for motor vehicle accidents at urban junctions (no other type of road users involved) is somewhat different from model type (1):

$$AR = a * (I_M + I_m)^b * \left[\frac{I_m}{(I_M + I_m)} \right]^c \quad (21)$$

- AR: accident rate
- I_M: number of incoming motor vehicles from MAJOR road
- I_m: number of incoming motor vehicles from minor road
- a, b, c: estimated parameters

The most important difference has to do with the factor which introduces the proportion of the vehicles from the minor road in relation to the total incoming flow. The Swedish model has been fitted for many types of junctions:

| Number of arms | three-arm | | | | | |
|---|--------------------|------|------|--------------------|------|------|
| | 50 | | | 70 | | |
| Speed limit (km/h) | | | | | | |
| Parameter | a*10 ⁻⁸ | b | c | a*10 ⁻⁸ | b | c |
| Priority | 45 | 1.45 | 0.50 | 597 | 1.25 | 0.45 |
| Signalized | 317 | 1.20 | 0.10 | 651 | 1.20 | 0.10 |
| Signalized, detection systems or separate phase for vehicles turning left | 176 | 1.20 | 0.10 | 418 | 1.20 | 0.10 |
| Roundabout | 232 | 1.20 | 0 | 332 | 1.20 | 0 |

| number of arms | four-arm | | | | | |
|---|--------------------|------|------|--------------------|------|------|
| speed limit (km/h) | 50 | | | 70 | | |
| parameter | a*10 ⁻⁷ | b | c | a*10 ⁻⁷ | b | c |
| priority | 14.8 | 1.45 | 0.60 | 164 | 1.25 | 0.55 |
| signalized | 97.2 | 1.20 | 0.20 | 173 | 1.20 | 0.20 |
| signalized, detection systems or separate phase for vehicles turning left | 49.9 | 1.20 | 0.20 | 94 | 1.20 | 0.20 |
| roundabout | 30.8 | 1.20 | 0 | 44 | 1.20 | 0 |

Table 6.5 *Estimated parameters in the Swedish model (type 21)*

Models which are more complicated can be used to relate the number of accidents to detailed characteristics of the junction, e.g. different types of medians (CROW, 1997) or the number of arms of a junction:

$$A = c * Q_1^a * Q_2^b * K \quad (22)$$

K: design element

Sometimes flows Q_1 and Q_2 are added instead of multiplied.

The Nordic countries are developing models in which the influence of bicycle flows is incorporated.

Cyclists and pedestrians

Brüde & Larsson (1993) have analyzed accidents at junctions which are situated in 30 Swedish urban areas with more than 25,000 inhabitants. They were especially interested in accidents concerning cyclists and pedestrians. Their analysis comprised 432 accidents with cyclists on 377 junctions, and 165 accidents with pedestrians on 285 junctions. Only junctions with pedestrian or bicycle flows of more than 100 per day have been selected.

Brüde & Larsson fitted a model of type (1), taking the entering motor vehicles as Q_1 and the number of crossing cyclists or pedestrians as Q_2 . A pedestrian or cyclist who crosses two times at a junction (e.g. if he/she has to cross two carriageways in order to turn left) is counted as two pedestrians or cyclists. The model for the accident rate of pedestrians is:

$$AR_{ped.} = 0.0201 * Q_{motorv.}^{0.50} * Q_{ped.}^{-0.28} \quad (23)$$

$AR_{ped.}$: number of accidents with pedestrians per million crossing pedestrians

$AR_{motorv.}$: number of accidents with motorvehicles per million passing motorvehicles

The model for the accident rate concerning accidents with cyclists is:

$$AR_{cyclist} = 0.0494 * Q_{motorv.}^{0.52} * Q_{cyclist}^{-0.35} \quad (24)$$

$AR_{cyclist}$: number of accidents with cyclists per million crossing cyclists

Roundabouts

Brüde & Larsson (1996) used another model for accidents with cyclists at urban roundabouts:

$$A_{cyclist} = 0.0000180 * Q_{motorv.}^{0.52} * Q_{cyclist}^{0.65} \quad (25)$$

$A_{cyclist}$: number of accidents with cyclists

This model was derived from Swedish data and was tested successfully by using Danish and Dutch data.

Van Minnen (1995) showed that the number of injury accidents at roundabouts is proportional to the number of entering motor vehicles. This applies to the total number of injury accidents, and to the number of injury accidents with bicycles/mopeds.

United Kingdom

The Transport Research Laboratory has recently reported about an extensive research into the (number of) accidents at different types of urban junctions:

- three-arm priority junctions
Summersgill et al. (1996) used data from 980 three-arm priority junctions. The total number of accidents at these junctions amounted to 2699 in a period of five years. The biggest part of the junctions has a speed limit of 30 mph, a smaller part has a speed limit of 40 mph.
- three-arm signalized junctions
Taylor et al. (1996) has investigated 221 tree-arm signalized junctions at which 2262 accidents occurred in a six-year period.
- four-arm priority junctions and staggered junctions
Layfield et al, (1996) selected 300 junctions (2917 accidents). The junctions have either a 40 mph limit or a 30 mph limit.

Many geometrical and other characteristics of each type of junction have been filed. The data about the vehicle flows were divided into the six possible flows at three-arm junctions and the twelve possible flows at four-arm junctions.

All fitted models are of model type (20) or of the following type:

$$A = I^\alpha * p^\beta * e^{\Sigma \gamma X} \quad (26)$$

- A: number of accidents
- I: number of entering vehicles on major and minor road
- p: percentage of the flow on the minor road
- α : estimated parameter
- β : estimated parameter
- γ : estimated parameter
- X: geometrical or technical element

These models require a high level of accuracy of the input data. In this case special attention has been paid to the inaccuracy of the flow data (Summersgill et al., 1996; page 31). Dozens of models were fitted, for the total number of accidents, for different types of accidents, and for types of accidents related to specific characteristics of a junction. Unfortunately the researchers have not given a clue for road designers to find their way in the many models. Much basic information is available; but a lot of effort should be undertaken to make it applicable for the road designer.

Denmark

The Danish Road Directorate (1995) fitted a model of type (20) using data from 1036 major urban junctions. Table 6.6 shows the parameters a, b and c for accidents with injury, for different types of junctions.

| Accidents with injury | Parameters in model (1) | | |
|------------------------|-------------------------|------|------|
| | c | a | b |
| Type of junctions | | | |
| Three arms, priority | $2.98 \cdot 10^{-6}$ | 0.81 | 0.52 |
| Three arms, signalized | $7.04 \cdot 10^{-8}$ | 1.36 | 0.32 |
| Four arms, priority | $1.68 \cdot 10^{-4}$ | 0.36 | 0.58 |
| Four arms, signalized | $8.62 \cdot 10^{-5}$ | 0.52 | 0.47 |

Tabel 6.6 *Danish parameters in model type (20)*

Other models have been developed taken into account several geometrical and other characteristics of junctions. However these more complicated models did not really show better results than model type (20). For this reason model type (20) will be applied.

Results from SAFESTAR

Starting from the Danish models of type (20) and the Swedish models (21), 23, and (24), SAFESTAR aimed at testing these models using data from other countries, viz. the Netherlands, France, and the Czech Republic. Furthermore the Danish and Swedish models have been compared with each other for a few combinations of input values. Finally recommendations about the application of certain types of junctions have been formulated.

The Swedish and Danish models

The Swedish model type (21) for the accident rates of motor vehicle accidents shows that a growing number of incoming motor vehicles results in a higher accident rate. This finding is valid for all types of junctions (see also table 6.5); see Figures 6.2A and 6.2B.

In the models (23) and (24) respectively increasing numbers of crossing cyclists and pedestrians result in *lower* accident rates for cyclists and pedestrians. At the same time these models imply that the absolute number of accidents with cyclists and pedestrians is increasing when the cyclists' and pedestrians' flows grow (and also increasing when the number of incoming motor vehicles grows); see also figures 6.3 and 6.4.

The Danish model type (20) shows a different result compared to the Swedish model type (21). In this comparison the same input values have been used. For four-arm junctions the accident rates of motor vehicle accidents show an accident rate which is nearly constant, independent of the number of incoming motor vehicles. The increasing accident rates of the three-arm junctions are comparable to the results of the Swedish model.

The accident rates in these Swedish and Danish models have about the same level.

Both Denmark and Sweden are using the same type of models for accidents with cyclists (type 24). Therefore the differences in the results are small (both models show a decreasing accident rate and an increasing number of accidents when the number of cyclists increases). The accident level for this type of accident is apparently higher in Denmark than in Sweden.

Testing the models with data from other countries

The models to be tested have a rather simple structure, and the input seems to be of a simple nature as well. However, input data about the number of cyclists appeared to be hardly ever available, except for some junctions in the Netherlands. So most of the testing concentrated on the models of type (20) and (21).

Numbers of accidents with motorvehicles were available for five different types of junctions in the Netherlands. Both these numbers and the accident rates have been compared to the predicted values of the Danish and Swedish models (models 20 and 21). The predicted number of accidents by the Swedish model showed a reasonably good fit, while the Danish model consistently resulted in much too high numbers. However, the Danish model includes accidents with unprotected road users as well. See also Table 6.7 for a summary of the results.

Accidents with cyclists are overestimated by both the Swedish and the Danish models (type 24). Table 6.8 shows a clear overestimation for all types of junctions, except for the four-arm signalized junction with a speed limit of 70 km/h.

The French data only stemmed from four-arm signalized junctions. The description about the type of signalization seemed to be somewhat incomplete. That is why the Swedish model has been used for two different assumptions: if the signalization at the junction is of a simple type (no detection systems and no separate phase for vehicles turning left as well) then the accident numbers and the accident rate are predicted quite well. But if the assumption is that the signalization is equipped with those features, then the model fits badly. Table 6.9 shows the results.

| | 3P50 | 3S50 | 4P50 | 4S50 | Total50 | 4S70 |
|---|-------|-------|-------|-------|---------|-------|
| number of junctions | 95 | 24 | 36 | 49 | 204 | 19 |
| number of observed accidents | 71 | 27 | 44 | 116 | 258 | 121 |
| Sw. model: predicted number of accidents | 50.4 | 24.3 | 54.3 | 127.7 | 256.7 | 182.3 |
| Dan. model: predicted number of accidents | 84.3 | 66.8 | 50.7 | 155.7 | 357.5 | 105.1 |
| observed accident rate | 0.052 | 0.034 | 0.094 | 0.075 | - | 0.112 |
| Sw. model: predicted accident rate | 0.037 | 0.031 | 0.116 | 0.083 | - | 0.169 |
| Dan. model: predicted accident rate | 0.061 | 0.085 | 0.109 | 0.101 | - | 0.098 |

3P50: three-arm priority junction, speed limit 50 km/h
3S50: three-arm signalized junction, speed limit 50 km/h
4P50: four-arm priority junction, speed limit 50 km/h
4S50: four-arm signalized junction, speed limit 50 km/h
4S70: four-arm signalized junction, speed limit 70 km/h

Table 6.7 *Comparison between observed and predicted number of accidents and accident rates (motor vehicles only) for a number of Dutch junctions*

The Czech junctions have a speed limit of 60 km/h. To meet this condition, the Swedish model for 70 km/h was used. As for the French junctions, the prediction was made for two assumptions: signalization systems with and without detection systems or a separate phase for vehicles turning left. The best fit appeared to result from the assumption of a simple signalization system; see also Table 6.10.

Recommendations for applying different types of junctions

Brüde & Larsson (1998) have calculated the differences between the application of different types of junctions in the same conditions (number of incoming motor vehicles, proportion of the flow from the minor road). These differences in the number of accidents can be translated to the costs of these accidents. If a certain type of junction will save accident costs compared to an ordinary priority junction, then the application of the safer type will be profitable when rebuilding such a junction. The expected future accident costs of the existing type are higher than the expected costs of the safer type. This approach resulted in the following table 6.11:

| | 3P50 | 3S50 | 4P50 | 4S50 | 4S70 | Total |
|---|------|------|------|------|------|-------|
| number of junctions | 15 | 4 | 1 | 1 | 3 | 24 |
| number of observed accidents | 0 | 6 | 0 | 0 | 18 | 24 |
| Sw. model: predicted number of accidents | 19.0 | 13.5 | 1.4 | 1.2 | 10.7 | 45.8 |
| Dan. model: predicted number of accidents | 15.7 | 17.8 | 1.0 | 1.0 | 16.1 | 51.6 |

3P50: three-arm priority junction, speed limit 50 km/h
3S50: three-arm signalized junction, speed limit 50 km/h
4P50: four-arm priority junction, speed limit 50 km/h
4S50: four-arm signalized junction, speed limit 50 km/h
4S70: four-arm signalized junction, speed limit 70 km/h

Table 6.8 *Comparison between observed and predicted number of bicycle accidents and bicycle accident rates for a number of Dutch junctions*

| | 4S50 |
|--|-------|
| number of junctions | 19 |
| number of observed accidents | 185 |
| Sw. model: predicted number of accidents (simple traffic signals) | 190.6 |
| Sw. model: predicted number of accidents (signals with a detection system or a separate phase for vehicles turning left) | 98.2 |
| observed accident rate | 0.163 |
| Sw. model: predicted accident rate (simple traffic signals) | 0.168 |
| Sw. model: predicted accident rate (signals with a detection system or a separate phase for vehicles turning left) | 0.087 |

4S50: four-arm signalized junction, speed limit 50 km/h

Table 6.9 *Comparison between observed and predicted number of accidents and accident rates (only motor vehicles involved) for a number of French junctions*

| | 3P60 | 3S60 | 4P60 | 4S60 | Total |
|--|-------|-------|-------|-------|-------|
| number of junctions | 29 | 21 | 20 | 21 | 91 |
| number of observed accidents | 83 | 113 | 119 | 173 | 488 |
| Sw. model: predicted number of accidents (simple traffic signals) | 78.0 | 79.6 | 121.5 | 210.7 | 489.8 |
| Sw. model: predicted number of accidents (signals with a detection system or a separate phase for vehicles turning left) | 78.0 | 51.0 | 121.5 | 114.7 | 365.2 |
| observed accident rate | 0.104 | 0.156 | 0.236 | 0.224 | - |
| Sw. model: predicted accident rate (simple traffic signals) | 0.097 | 0.110 | 0.241 | 0.272 | - |
| Sw. model: predicted accident rate (signals with a detection system or a separate phase for vehicles turning left) | 0.097 | 0.070 | 0.241 | 0.148 | - |

3P60: three-arm priority junction, speed limit 60 km/h
3S60: three-arm signalized junction, speed limit 60 km/h
4P60: four-arm priority junction, speed limit 60 km/h
4S60: four-arm signalized junction, speed limit 60 km/h

Table 6.10 *Comparison between observed and predicted number of accidents and accident rates (only motor vehicles involved) for a number of Czech junctions*

| | Incoming motor vehicles per day | | | | | | | | |
|---|---------------------------------|---------|---------|----|---------|--------------|---------|---------|--------------|
| | 5 | | | 15 | | | 30 | | |
| proportion of motor vehicles coming from minor road | 5 | 20 | 50 | 5 | 20 | 50 | 5 | 20 | 50 |
| three-arm junction 50 km/h | - | - | - | - | - | S+ R | - | S+ | S+ R S |
| four-arm junction 50 km/h | - | - | R | - | R S+ | R S+ S | S+ R | R S+ | R S+ S |
| three-arm junction 70 km/h* | - | - | R | - | R S+ | R S+ | - | R S+ | R S+ S |
| four-arm junction 70 km/h* | - | R S+ | R S+ | R | R S+ | R S+ S | R S+ | R S+ | R S+ S |

-: replacement is not profitable
R: roundabout; S: signalized junction; S+ signalized junction with detection system or a separate phase for vehicles turning left
*: at these roads roundabouts usually have a speed limit of 50 km/h

Table 6.11 *Type of junction which is recommended according to outcome of the Swedish model*

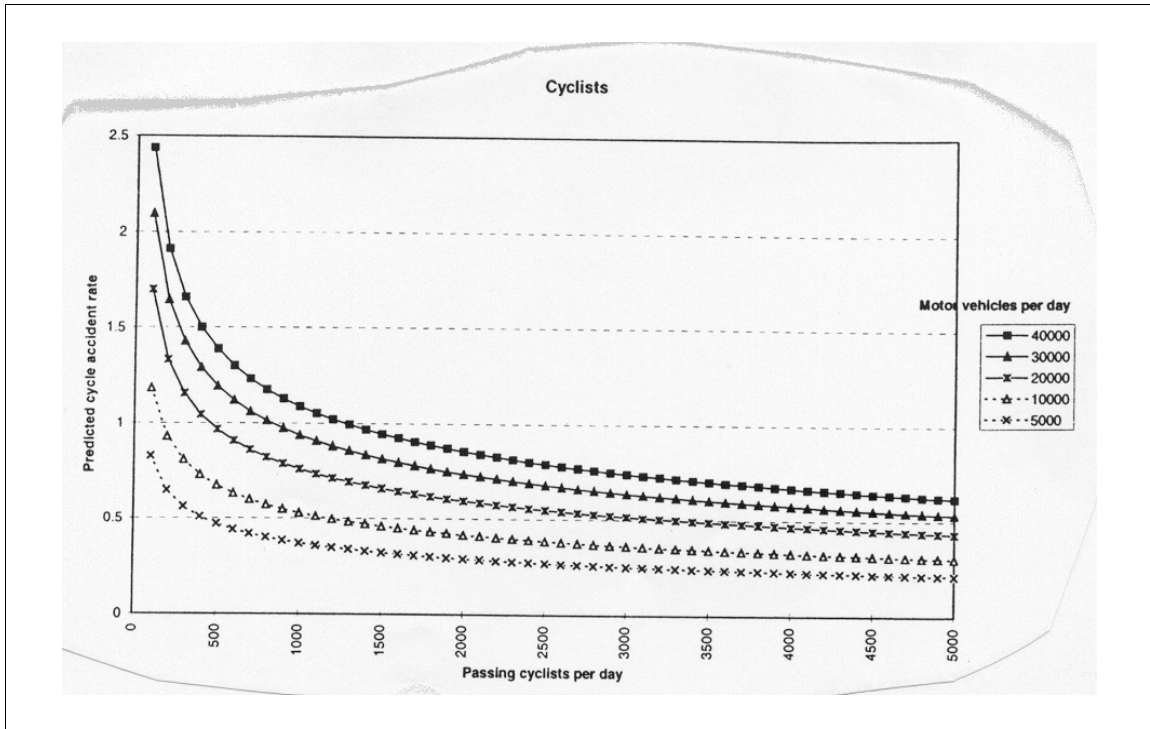


Figure 6.2A Accident rates (accidents with injury) as a result of the Swedish model, for roads with a speed limit of 50 km/h

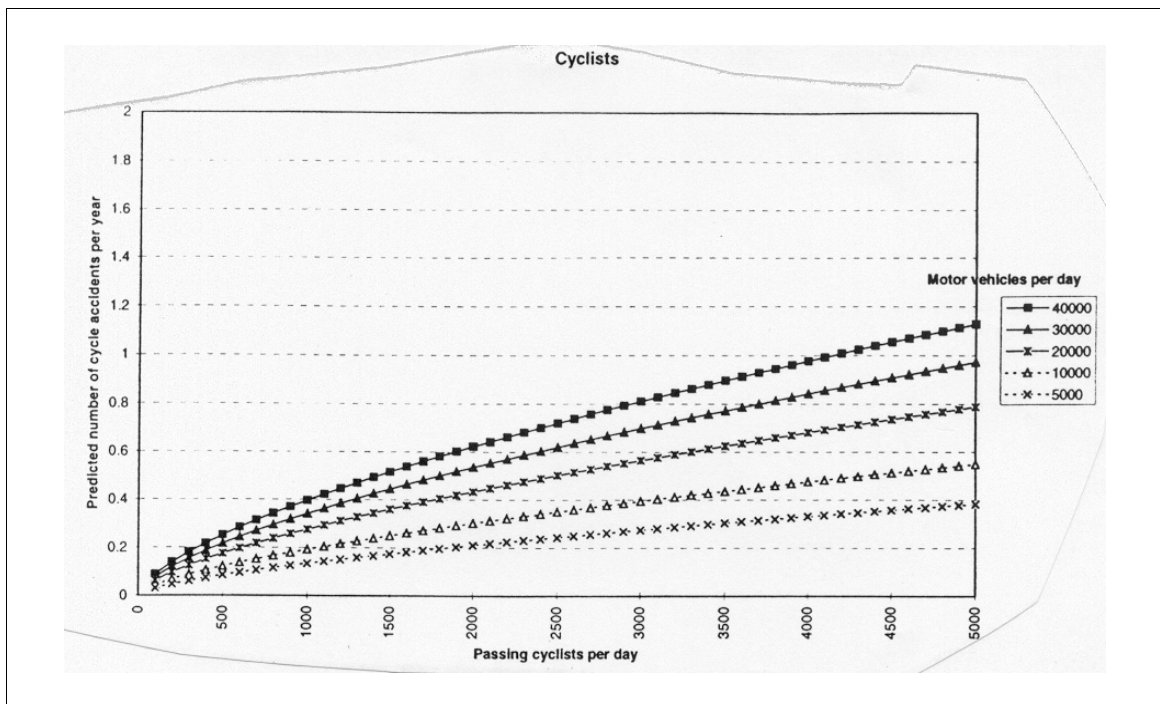


Figure 6.2B Accident rates (accidents with injury) as a result of the Swedish model, for roads with a speed limit of 70 km/h

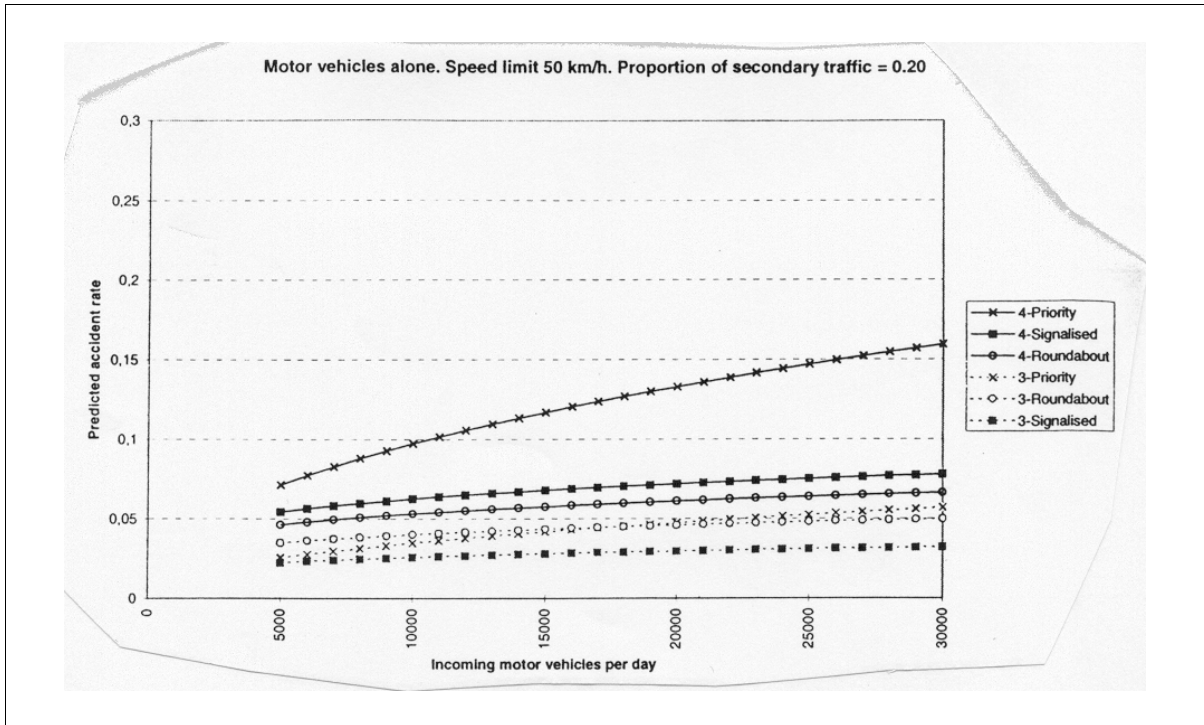


Figure 6.3 Accident rates (accidents with cyclists involved) as a result of the Swedish model

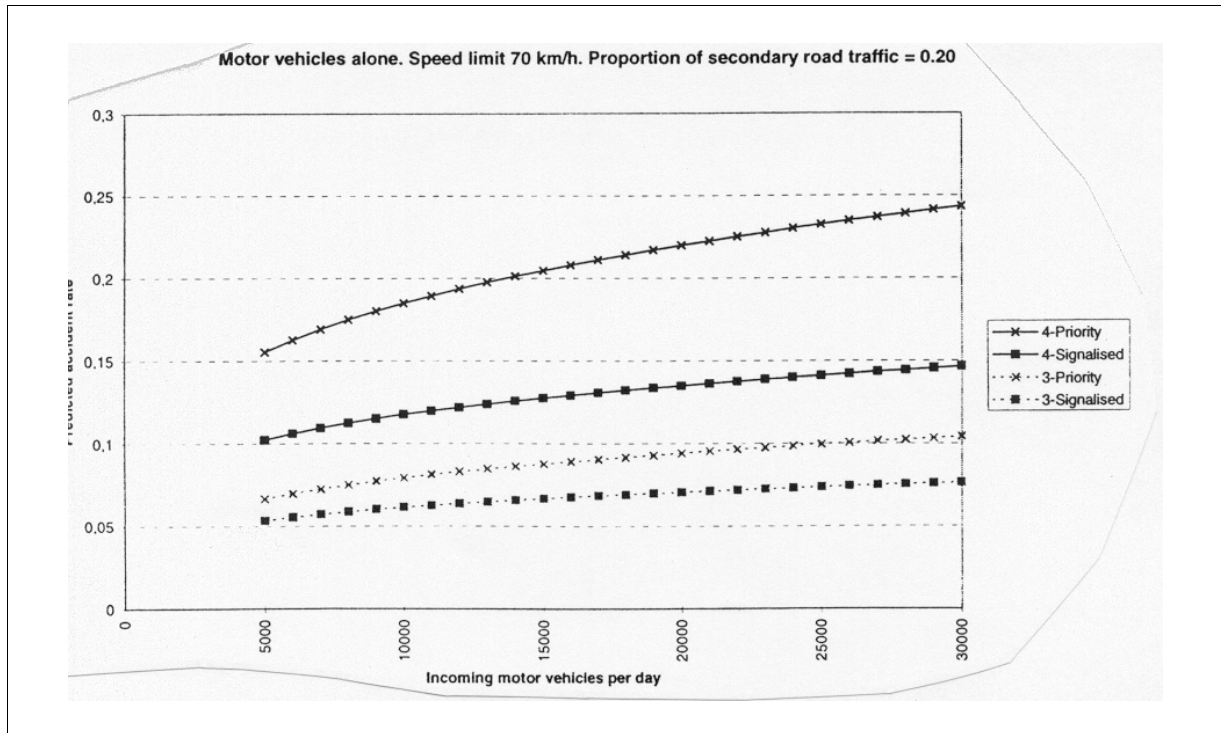


Figure 6.4 Number of accidents (accidents with cyclists involved) as a result of the Swedish model

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