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Safety aspects related to low noise road surfaces

Rune Elvik
Poul Greibe

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Preface

This report documents work package 3.1 of the project SILVIA (Silent roads), funded by the European Commission, The Research Council of Norway, and the Norwegian Public Roads Administration. The subject of the report is safety aspects related to porous asphalt, although other types of road surface treatments that may affect traffic noise are briefly mentioned.

The report has been jointly written by Rune Elvik, Institute of Transport Economics, and Poul Greibe, Atkins Denmark. Project manager for SILVIA at the Institute of Transport Economics has been Kjartan Sælensminde. Valuable comments on earlier drafts of the report have been given by (alphabetically):

Hans Bendtsen, Atkins Denmark
Davy Decock, Belgian Road Research Centre
Guy Descornet, Belgian Road Research Centre (project manager of SILVIA)
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We extend our gratitude for the comments received. Any remaining errors remain the responsibility of the authors.

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Institute of Transport Economics

Sønneve Ølnes
Acting Managing Director

Marika Kolbenstvedt
Head of department

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Summary:

Safety aspects related to low noise road surfaces

This report summarises current knowledge regarding safety aspects of low noise road surfaces, in particular porous asphalt. Porous asphalt is used in many European countries, mainly on motorways, as a measure to reduce traffic noise and increase road capacity, particularly during rain.

Studies that have evaluated the effects of porous asphalt on accidents and on risk factors associated with accident occurrence have been retrieved by means of a systematic search. Only six studies, containing a total of eighteen estimates of effect were regarded as suitable for a meta-analysis of effects on accidents. Most of these studies have not controlled adequately for confounding factors; hence their results are highly uncertain. The summary estimates of the effect of porous asphalt on accidents do not indicate that there are statistically significant changes in the number of accidents.

Effects of porous asphalt on risk factors were surveyed for nine different risk factors. Four of these factors are favourably affected by porous asphalt, three are adversely affected, and there is no clear effect on two risk factors. The strength of effects on risk factors is poorly known. The effects on accidents cannot be predicted on the basis of effects on risk factors.

The main conclusion is that more research is needed in order to determine the effects of porous asphalt on road safety. It is, however, clear that porous asphalt does reduce traffic noise.

Effects on skid resistance and road safety of other road surface treatments were surveyed. It was concluded that there is, in general no conflict between providing good skid resistance and low traffic noise. Moreover, it was found that improving skid resistance reduces the number of road accidents.

The report can be ordered from:
Institute of Transport Economics, PO Box 6110 Etterstad, N-0602 Oslo, Norway
Telephone: +47 22 57 38 00   Telefax: +47 22 57 02 90

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Sammendrag:

Trafikksikkerhetsaspekter ved støysvake vegdekker

Denne rapporten oppsummerer foreliggende kunnskap om trafikksikkerhets-aspekter ved støysvake vegdekker, spesielt drensasfalt. Drensasfalt brukes mye som vegdekke i Europa, spesielt på motorveger. Tiltakets hovedformål er å redusere trafikkstøy og øke vegens kapasitet. Det har imidlertid også interesse å vite hvordan drensasfalt påvirker trafikksikkerheten.

Det er utført en systematisk litteraturstudie av studier som har undersøkt virkninger av drensasfalt på antall ulykker eller på risikofaktorer som har sammenheng med ulykkestall. Resultatene av studier som har undersøkt virkninger på ulykker er oppsummert ved hjelp av meta-analyse. I meta-analysen inngikk seks undersøkelser med til sammen 18 resultater. Meta-analysen tyder ikke på at drensasfalt har statistisk signifikante virkninger på antall ulykker.

Virkningene av drensasfalt på i alt ni ulike risikofaktorer er undersøkt ved hjelp av en litteraturstudie. Studien fant at fire av de ni faktorene påvirkes i gunstig retning, tre påvirkes i ugunstig retning og to av risikofaktorene påvirkes ikke av drensasfalt. Det foreligger sparsomt med opplysninger om hvor store effekter drensasfalt har på de enkelte risikofaktorer. Virkningen av drensasfalt på ulykkene kan ikke predikeres på grunnlag av kunnskap om virkningen på risikofaktorer.

Hovedkonklusjonen i rapporten er at det trengs mer forskning for å fastslå hvordan drensasfalt påvirker trafikksikkerheten.

Det er også gjort en gjennomgang av litteratur om andre tiltak rettet mot vegdekket enn det å legge drensasfalt. Det er fullt mulig å legge vegdekker som både gir god friksjon og lavt støynivå. Vegdekker med god friksjon gir også lavere ulykkesrisiko enn vegdekker med dårlig friksjon. Man kan følgelig oppnå en forbedring både av trafikksikkerheten og av støyforholdene gjennom tiltak rettet mot vegdekket.

Rapporten kan bestilles fra:
Transportøkonomisk institutt, Postboks 6110 Etterstad, 0602 Oslo
Telefon: 22 57 38 00   Telefax: 22 57 02 90

1 Introduction

1.1 Background

This report summarises current knowledge regarding safety aspects of low noise road surfaces, with particular emphasis of porous asphalt. Other types of road surface treatments that may also reduce traffic noise are only briefly discussed. The report documents task 3.1 in Work Package 3 of the SILVIA-project (SILVIA = Silenda Via = Silent Roads). There are four main objectives of SILVIA (Sustainable Road Surfaces for Traffic Noise Control). These are:

1. To develop a classification procedure combined with a conformity-of-production testing method. It will start from existing measurement methods, improve some of them and possibly develop new ones.
2. To test and specify road construction and maintenance techniques that would achieve satisfactory durability of the acoustic performances while complying with other requirements of sustainability like safety, pollution and mobility.
3. To develop a procedure for cost-benefit analysis of noise abatement measures, with emphasis of low noise road surfaces.
4. To issue a European Guidance Manual on the Utilisation of Low-Noise Road Surfaces designed to help decision makers to rationally plan noise abatement measures, integrating low-noise surfaces with other noise control measures.

Workpackage 3 deals mainly with the third objective and aims at developing methods for cost-benefit analysis of noise control actions, with main emphasis on low noise road surfaces.

The objective of task 3.1 is to provide the best current estimate of the effect of low noise road surfaces on road safety, as well as identify factors that influence the size of the safety effects. This report forms the output from task 3.1 in Workpackage 3 (Deliverable D03).

1.2 Porous asphalt

The most commonly used asphalt type with regard to low noise is porous asphalt. Porous asphalt differs from ordinary dense asphalt concrete by having an open structure with approximately 20-25% air filled pores. The open structure of porous asphalt reduces traffic noise, drains water from the road surface and reduces thermal conductivity. These characteristics of porous asphalt can have an effect on road safety.

Porous asphalt has been used on roads since the mid 1980's and is today widely used in some EU-countries, e.g. The Netherlands, Belgium, France, Austria, Italy and England. Porous asphalt has been used particularly on motorways. The main reasons for its use include its ability to reduce traffic noise and increase road capacity. During rainfall, the capacity of roads with porous asphalt is not greatly reduced, since the water is not accumulated on the road surface but drained away. With less water on the road surface, splash and spray is reduced, visibility is improved and the risk of aquaplaning is greatly reduced. In darkness light reflection from water accumulated on the road surface is reduced. Effects on road safety are, however, not very well known. Therefore, a systematic review of studies that can shed light on road safety effects of porous asphalt has been made.

1.3 Other low noise road surface treatments

In addition to reviewing the road safety effects of porous asphalt, the report briefly discusses other road surface treatments that can affect both noise and road safety. The objective of this discussion is to determine whether a trade-off has to be made between providing for high skid resistance, and hence a high level of road safety, and reducing traffic noise.

1.4 Research problems

The main research problems that this report seeks to answer are:

1. What are the effects on road safety of porous road surfaces, or other surface treatments that can reduce traffic noise?
2. Do the effects on road safety of low noise road surfaces vary according to accident severity and road surface condition?
3. Do the effects on road safety of low noise road surfaces vary between different countries?
4. How long do the effects on road safety of low noise road surfaces last?

The objective of the report is to summarise evidence from evaluation studies in order to answer these questions. It is recognised, however, that evidence from available evaluation studies may be inconclusive with regard to some of these questions. In addition to studies that have evaluated effects on accidents, studies that have evaluated the effects of low noise road surfaces on various risk factors associated with accident occurrence will therefore be surveyed.

1.5 Study approach

The approach taken in the study can be briefly described as follows.

A systematic literature review has been undertaken. This review is to a large extent based on a previous literature survey (Greibe 2000). That survey indicated that only a few studies have evaluated the effects on road safety of low noise road surfaces. Furthermore, it indicated that the findings of the evaluation studies are conflicting and difficult to summarise. It was therefore decided to collect additional information from the partners of the SILVIA-consortium.

A systematic review of evidence from evaluation studies is presented. This review includes a meta-analysis of some of the studies that have been retrieved. The next chapter describes how the literature search was conducted and how relevant studies were identified.

2 Searching for evaluation studies

2.1 Literature search

A search was made of the TRANSPORT literature database using the combination of «road safety» and «road surfaces» as search terms. In addition, a previous literature review (Greibe 2000) was used as a source. Table 1 lists the studies that were retrieved and that have evaluated the effects on accidents of road surface characteristics or treatments and have been published after 1990. Studies are listed chronologically.

Table 1: List of studies that have evaluated the safety effects of road surface treatments, retrieved in literature search

Study number	Authors	Year of publication	Country	Treatment evaluated
1	Wong	1990	United States	High friction surface
2	Craus et al	1991	Israel	Ordinary resurfacing
3	Roe et al	1991	Great Britain	High friction surface
4	Tromp	1993	Netherlands	Porous asphalt
5	Hauer et al	1994	United States	Ordinary resurfacing
6	Herbst, Holzhammer	1995	Austria	Porous asphalt
7	Start, Kim, Berg	1996	United States	Treatment of rutting
8	Bonnot	1997	France	Porous asphalt
9	Cairney	1997	Australia	High friction surface
10	Sjölinder et al	1997	Sweden	Rutting and evenness
11	Brailly	1998	France	Porous asphalt
12	Leden et al	1998	Finland	Ordinary resurfacing
13	Bendtsen et al	2002	Denmark	Porous asphalt
14	Commandeur et al	2002	Netherlands	Porous asphalt
15	Ihs, Velin, Wiklund	2002	Sweden	Rutting and evenness
16	Velin, Öberg	2002	Sweden	Ordinary resurfacing

Source: TØI report 680/2003

A total of 16 studies were retrieved. Four main types of road surface treatments have been evaluated by these studies:

1. Ordinary resurfacing of roads
2. Laying of high friction road surfaces
3. Treatment of rutting or unevenness
4. Laying of porous asphalt

In this report, *only studies that state explicitly that a porous road surface has been laid have been included*. This means that the majority of the studies listed in Table 1 have not been included in the systematic review presented in chapter 4.

In addition to studies that have evaluated the effects of porous asphalt on accidents, studies that have evaluated the effects of porous asphalt on various risk factors associated with accidents have been included. The same sources were used in this search as in the search for studies that have evaluated the effects of porous asphalt on accidents. Table 2 lists the studies that were retrieved. It will be noted that some of the studies listed in Table 1 are listed in Table 2 as well. These are studies that have evaluated the effects of porous asphalt both on accidents and on selected risk factors.

Table 2: List of studies that have evaluated the effects of porous asphalt on risk factors, retrieved in literature search

Study number	Authors	Year of publication	Country	Risk factors evaluated
1	Ragnøy	1989	Norway	Aquaplaning, splash and spray, friction, light reflection
2	Delanne et al	1991	France	Friction, stopping distance
3	Bonnot	1997	France	Friction, thermal conductivity
4	Litzka	1997	Austria	Water permeability
5	Bendtsen et al	2002	Denmark	Water permeability, friction, speed
6	Edwards	2002	Great Britain	Speed

Source: TØI report 680/2003

In addition, a number of studies that were not found in the literature research but are well known have been included in the evaluation of risk factors. These are listed in table 3.

Table 3: List of additional studies that have evaluated risk factors.

Study number	Authors	Year of publication	Country	Risk factors evaluated
7	Nicholls and Daines	1992	Great Britain	Splash and spray
8	PIARC	1992	International	Friction, winter maintenance,
9	Norrts	1996	Netherlands	Winter maintenance
10	Nicholls	1997	Great Britain	Splash and spray, friction, light reflection, rutting
11	Swart	1997	Netherlands	Friction, speed, capacity
12	Leden et al	1998	Sweden	Resurfacing
13	Elvik and Vaa	2003	Norway	Resurfacing, surface condition

Source: TØI report 680/2003

A total of 13 studies have been retrieved. There does not seem to be very much evidence regarding the effects of porous asphalt on various risk factors associated with accidents.

2.2 Experiences within the SILVIA consortium

In parallel to the literature review, a request for national experiences regarding porous asphalt and safety has been sent to partners in the SILVIA consortium. Only a few new references were found, but accident data from porous asphalt road sections were identified and one new accident analysis was made based on data from a German motorway. The data for this study are found in an Excel spreadsheet (BASt safety study.xls), forwarded by Nina Sliwa of the Bundesanstalt für Strassenwesen (BASt), partner in the SILVIA project.

In addition, data have been provided concerning selected sections of an Italian motorway where Italgrip have been applied. These data were provided by the producer of Italgrip (Silvio Spinoglio), partner in the SILVIA project. Italgrip is a road surface treatment, which is primarily intended to increase road surface skid resistance, but has been found to reduce traffic noise as well (Henry, 2000). Italgrip sections have therefore been included in the systematic review of evidence.

3 Critical assessment of evaluation studies

3.1 Assessment of study quality

An essential element of any systematic review of evidence from evaluation studies is a critical assessment of the quality of studies. The quality of road safety evaluation studies varies substantially, and the findings of such studies have been found to be associated with study quality (Elvik 1997). A formal assessment of study quality has therefore been conducted, based on the following criteria:

1. The specification of the road surface conditions to which estimates of effect apply.
2. The specification of the severity of accidents to which estimates of effect apply.
3. The extent to which a study controls for confounding factors that may influence estimates of the effects of porous asphalt.
4. Whether a study has used appropriate statistical techniques to analyse data.

Each of these points will be elaborated.

The effects of a porous road surface are most clearly noticed by road users during rain or when the road surface is wet. The drainage of water means that there is much less water on the road surface, which reduces splash and spray and improves visibility. One would therefore expect the road safety effect of porous asphalt to be greater on wet roads than on dry roads (a larger reduction in accidents). In winter, the reduced thermal conductivity of porous asphalt means that water freezes more easily on it than on dense road surfaces. This could lead to lower skid resistance during winter. Ideally speaking, a study should therefore identify the effects of porous asphalt on: (a) A dry road surface, (b) A wet road surface, and (c) A road surface which is fully or partly covered by snow or ice, including an estimate of how porous asphalt affects the frequency of occurrence of such surface conditions.

The costs to society of road accidents, and the suffering they bring to victims, depend strongly on accident severity. The objective of Work Package 3 of SILVIA is to develop a method for cost-benefit analysis of noise abatement measures, in particular low-noise road surfaces. It is therefore important to know if the effects of porous asphalt vary according to accident severity. Ideally speaking, an evaluation study ought to specify effects for: (a) Fatal accidents, (b) Accidents involving serious injury, (c) Accidents involving slight injury, and (d) Accidents leading to property-damage-only. Knowing accident severity is important, since the prevention of property-damage-only accidents is rather less important than the prevention of fatal and injury accidents. In this report, estimates of safety effect will be stated in terms of the percentage change in the expected number of accidents.

Road accidents are usually the outcome of a highly complex interaction of a large number of risk factors. Very many factors influence the number of accidents. In an evaluation study, we would ideally want to estimate the effects of a road safety measure only, and not of all the other factors affecting the number of accidents. Interpretation of study findings is difficult if we cannot be sure, or at least have good reasons to believe, if the observed changes in the number of accidents were caused by the road safety measure or by other factors. The factors whose effects we want to control for are usually referred to as confounding factors (Elvik 2002). In principle, the number of potentially confounding factors in road safety evaluation research is infinite. Perfect control for confounding factors can only be attained by conducting experiments; that is randomised controlled trials. Unfortunately, very few road safety evaluation studies rely on an experimental study design. Control for confounding factors in most of these studies is therefore incomplete.

The most practical way to assess the quality of a study with respect to control for confounding factors is to list the most important confounding factors and to check for each of them whether or not the study controlled for that factor. In before-and-after studies, the most important potentially confounding factors include: (a) *Regression-to-the-mean*, which means that if sites have been selected for treatment because of an abnormally high number of accidents, one may expect the number of accidents to go down even if the treatment has no effect, (b) *Long-term trends* in the number of accidents, which refers to a tendency, observed during several years, for the number of accidents to increase or go down, (c) *Site-specific changes in traffic volume*, departing from the overall trend for the region or the country as a whole (the overall trend of all factors influencing accidents, including traffic volume, are assumed to be captured by a comparison group), (d) *Other specific events*, such as the introduction of other road safety measures whose effects can be mixed up with the road safety measure that is of primary interest in a study.

In case-control studies or other studies employing a comparative cross-section design, it is rather more difficult to list the most important confounding factors than for before-and-after studies. Very many more confounding factors can upset the results of a case-control study than of a before-and-after study. Case-control studies are notorious for their proneness to bias (Crombie 1996). In case-control studies, effects are usually estimated in terms of the accident rate ratio, rather than the number of accidents, which is the most common denominator for safety effects in before-and-after studies. Hence, the potentially confounding factors are all factors that can influence accident rates. These factors can be divided into three main categories: (A) *Total traffic volume*: Accident rates are not independent of traffic volume. Ideally speaking, therefore, mean traffic volume ought to be identical on case road sections and control road sections. (B) *Traffic composition*, which refers to how traffic is made up of small cars, large cars, motorcycles, pedestrians, and so on. Different mixes of types of vehicles and groups of road users tend to produce different accident rates. (C) *Road design and traffic control parameters*. These include type of road (motorway, non-motorway), number of lanes, speed limit, access control, alignment and a number of other factors, which have been found to be statistically associated with accident rates.

The use of appropriate statistical techniques to analyse accident data is essential for obtaining unbiased estimates of the effects of the road safety measure evaluated. An appropriate statistical technique is one that utilises all available data and is based on a correct set of assumptions with respect to the process that has produced the data. As far as accident occurrence is concerned, it is usually assumed that a count of accidents is the result of a generalised Poisson process. The statistical technique used to analyse the data should correctly model the essential characteristics of the generalised Poisson process.

Study quality has been assessed by means of these criteria. In principle, a numerical quality score could be assigned to each study based on these criteria. The scoring system shown in table 4 has been developed.

Each criterion used to assess study quality is scored on an ordinal scale. The overall scale based on a weighted combination of the four criteria is, however, treated as an approximation to an interval scale. The four criteria have been given weights that sum to 1.0. The maximum score a study can get is 8 (2 x 4), the minimum is 0. Scores between these numbers have been converted to a bounded scale ranging from 0 to 1. The overall quality of a study that scores 1 for road surface, 1 for accident severity, 1 for control for confounding factors and 2 for statistical analysis thus becomes: (1 x 0.2) + (1 x 0.2) + (1 x 0.5) + (2 x 0.1) = 0.2 + 0.2 + 0.5 + 0.2 = 1.1. The maximum score using weights is 2. Hence this study scores 0.55 on the (0, 1) scale.

Table 4: Scoring of study quality for studies that have evaluated the effects on road safety of porous asphalt or similar treatments.

Criterion	**Scores used**	**Weight given**
Road surface conditions	2 = dry, wet and wintry specified 1 = dry or wet specified 0 = conditions not specified	0.20
Accident severity	2 = all levels specified 1 = some levels specified 0 = not stated	0.20
Control for confounding	2 = all major factors controlled 1 = some major factors controlled 0 = no factors controlled	0.50
Statistical analysis	2 = appropriate techniques used 1 = not proper, re-analysis possible 0 = not proper, no re-analysis	0.10

Source: TØI report 680/2003

The high weight given to control for confounding factors reflects the fact that inadequate control of such factors tends to be the dominant source of error and misleading estimates of effect in road safety evaluation studies. A before-and-after study not controlling for regression-to-the-mean, for example, can overstate the effect of a measure by perhaps 30-50 percentage points (Elvik 1997).

3.2 The possibility of quantitative synthesis of evidence (meta-analysis)

A systematic review of evidence based on a set of studies is a critical examination and summary of the studies, based on criteria that are applied equally to all studies. A systematic review may include a meta-analysis, but such an analysis need not be part of a systematic review of evidence. A meta-analysis is a statistical analysis of estimates of effect provided by a set of studies, primarily for the purpose of producing a summary estimate of effect based on the set of estimates found in the studies included.

A meta-analysis may be informative whenever:

1. There are many estimates of effect.
2. The individual estimates of effect vary, but show a tendency for estimates based on large samples to come close to a common mean estimate of effect (the distribution of estimates of effect is unimodal).
3. A mean estimate of effect will accurately summarise the main tendency of the individual estimates of effect (the mean is not itself an outlying data point, strongly influenced by a single estimate of effect which differs greatly from all other estimates).

In order to perform a meta-analysis, two conditions must be fulfilled:

1. The individual estimates of effect should all be identically defined or be amenable to conversion to a common scale or denominator.
2. The standard error, or sampling variance, of each estimate of effect should be known.

Chapter 6 presents the results of a meta-analysis of studies of the effects on accidents of porous asphalt, which has been performed as part of this systematic review.

4 Systematic review of studies: effects on accidents

4.1 Tromp 1993

The evaluation study reported by Tromp (1993) is a comparison of the accident rate on Dutch motorways with porous asphalt to motorways with dense asphalt concrete. Table 5 shows some key data from the study.

Motorways were classified into those that have two lanes in each direction and those that have more than two lanes in each direction. In each group, the accident rate was estimated for motorways with porous asphalt and motorways with dense asphalt. The effect on safety of porous asphalt is indicated by the accident rate ratio:

$$\text{Accident rate ratio} = \frac{\left(\dfrac{\text{Number of accidents on motorways with porous asphalt}}{\text{Kilometres of driving on motorways with porous asphalt}}\right)}{\left(\dfrac{\text{Number of accidents on motorways with dense asphalt}}{\text{Kilometres of driving on motorways with dense asphalt}}\right)}$$

Table 5 shows the accident rate ratios for all accidents and injury accidents. The ratios show an inconsistent pattern. On motorways with two lanes in each direction, the accident rate for all accidents was higher on porous asphalt than on dense asphalt, whereas the injury accident rate was lower on porous asphalt than on dense asphalt. On motorways with more than two lanes in each direction, exactly the opposite pattern was found.

Table 5: Key data from Dutch study of motorways with porous or dense asphalt. Extracted from Tromp 1993

Type of road section	Key data	Dense asphalt	Porous asphalt	Accident rate ratio
2 lanes in each direction (all)	All accidents	4,538	380	
	Accidents on dry road surface	2,876	231	
	Accidents on wet road surface	1,041	117	
	Injury accidents (all)	318	18	
	Million vehicle km of travel	22970.4	1681.3	
	Accident rate (all accidents)	0.198	0.226	1.141
	Injury accident rate	0.0138	0.0107	0.775
More than 2 lanes (all)	All accidents	1,058	239	
	Accidents on dry road surface	699	171	
	Accidents on wet road surface	273	53	
	Injury accidents (all)	36	11	
	Million vehicle km of travel	5229,4	1401,9	
	Accident rate (all accidents)	0.202	0.170	0.842
	Injury accident rate	0.0069	0.0078	1.130

Source: TØI report 680/2003

Tromp (1993) notes that there were many differences between motorways with porous asphalt and motorways with dense asphalt. To eliminate the influence of these confounding factors, a set of matched pairs was formed, intended to be as homogeneous as possible. In each pair, one road section had dense asphalt, the other had porous asphalt. A total of 83 pairs were formed. The report presents the following information about these paired sections:

Table 6: Matched pairs of Dutch Motorway sections. From Tromp 1993

Data	Dense asphalt	Porous asphalt
Length (kilometres)	199.1	150.8
All accidents	433	367
Accidents on dry road surface	288	220
Accidents on wet road surface	110	111
Accidents, unknown road surface	35	36

Source: TØI report 680/2003

The number of vehicle kilometres of travel for the sample of matched pairs is not stated. Presumably, traffic volume was one of the variables used to form matched pairs. It therefore seems reasonable to assume that roads with dense asphalt and roads with porous asphalt were similar with respect to traffic volume.

In table 6, accidents have been specified according to road surface condition (dry or wet). Vehicle kilometres of travel have not been specified according to road surface condition. However, it is reasonable to assume that, in the long run, it does not rain more often on motorways with porous asphalt than on those with dense asphalt. The main criterion for introducing porous asphalt on Dutch motorways has been twofold: to reduce traffic noise and to increase capacity during rainy weather. If the assumption is made that a wet road surface occurs equally often on motorways with porous asphalt as on motorways with dense asphalt, an accident rate ratio can be estimated by using overall vehicle kilometres of travel as denominator. Relying on this assumption, the following estimates of effect have been extracted from this study for inclusion in a meta-analysis:

Table 7: Study results extracted from Tromp 1993

Specification of estimate of effect	**Estimate of effect (accident rate ratio)**
Motorways, two lanes, dry road, all accidents	1.097
Motorways, two lanes, wet road, all accidents	1.536
Motorways, two lanes, all surfaces, injury accidents	0.775
Motorways, many lanes, dry road, all accidents	0.913
Motorways, many lanes, wet road, all accidents	0.724
Motorways, many lanes, all surfaces, injury accidents	1.130
Matched pair of roads, dry road, all accidents	1.009
Matched pair of roads, wet road, all accidents	1.333

Source: TØI report 680/2003

An estimate of effect for all road surface conditions can be obtained in meta-analysis by combining the estimates for dry and wet road surfaces. Hence, only the estimates pertaining to each type of road surface condition have been extracted (except for injury accidents, for which only an overall estimate of effect can be extracted).

The part of the study that refers to all motorways scores 1 for road surface specification (winter is missing), 1 for specification of accident severity, 1 for control for confounding factors (number of lanes was controlled for and overall traffic volume was stated) and 2 for statistical analysis. This gives an overall score of 0.55. The matched pair study scores 1 for specification of road surface conditions, 0 for specification of accident severity (injury accidents and other accidents appear to be mixed up), 2 for control for confounding factors (matching is assumed to be perfect), and 2 for statistical analysis. Overall quality score then becomes 0.70.

4.2 Herbst and Holzhammer 1995

This study, presented as a paper during the 1995 PIARC conference, summarises Austrian experiences in using porous asphalt on motorways. The effect on the accident rate of porous asphalt is presented in a set of figures, tracking changes in accident rates from before to after the laying of porous asphalt. Based on these figures, the following injury accident rates have been derived (accidents per million vehicle kilometres, extracted from Figure 3 in Herbst and Holzhammer 1995):

Mean accident rate for dense asphalt (before) - Dry: 0.22

Mean accident rate for dense asphalt (before) – Wet: 0.06

Mean accident rate for porous asphalt (after) - Dry: 0.08

Mean accident rate for porous asphalt (after) -Wet: 0.03

The before and after periods have been defined, respectively, to years -8 to -4 and years +4 to +6, see Figure 3 in Herbst and Holzhammer 1995.

The figure also tracks the accident rate during winter, but the curve is difficult to read and has therefore not been included. Furthermore, the years during which porous road surfaces were being laid have been omitted. Based on the accident rates stated above, the following estimates of effect can be extracted:

Effect on dry road surfaces: 0.08/0.22 = 0.364

Effect on wet road surfaces: 0.03/0.06 = 0.500

The number of accidents underlying these estimates of effect is not stated. Moreover, the study does not describe study design in full detail. The study appears to be a before-and-after study not controlling for any confounding factors. The study has been scored 1 for specification of road surface condition, 1 for specification of accident severity, 0 for control for confounding factors, and 1 for statistical analysis (because the study does not present any proper analysis and estimates of effect had to be extracted from a figure). This gives an overall score of 0.25 on the 0 to 1 scale.

4.3 Bonnot 1997

This report is a comprehensive discussion of French experiences using porous asphalt. With respect to the effect on road safety, the study refers to another study (Brailly, 1998), to be discussed below. It does, however, quote estimates of accident rates for 555 km of motorway having porous asphalt and 2,541 km of motorway having dense asphalt. The estimated rates were more or less identical, 32.3 accidents per 100 million vehicle kilometres for porous asphalt and 33.0 for motorways with dense asphalt. This gives an estimate of effect of 32.3/33.0 = 0.979. The number of accidents underlying the estimated accident rates is not stated. This study is not identical to Brailly's study and does thus provide an independent estimate of the safety effect of porous asphalt.

The study states that the accident rates refer to both injury accidents and property-damage-only accidents. Road surface condition is not specified. The study scores 0 for specification of road surface conditions, 0 for specification of accident severity, 0 for control of confounding factors, but, given its very simple design, 2 for statistical analysis. This gives an overall quality score of 0.10 on 0 to 1 scale.

4.4 Brailly 1998

This French study measures the safety effect of resurfacing motorways with two different kinds of asphalt, porous asphalt and thin asphalt concrete. Only results from porous asphalt will be mentioned here. The study is a before-and-after study based on a total of 550 km of motorway where the pavement has been replaced with porous asphalt in the period 1979-1992.

Accident data up to a five-year period before and after were used. Accident data consisted of fatal, serious injury and slight injury accidents. In addition, data on weather conditions and traffic volume were collected along with general trends in accidents for French motorways.

Data were analysed by means of the numerical technique developed by Tanner (1958), which is very cumbersome and rarely used today. The technique cannot handle road sections with zero accidents (in the before or after period). Road sections that did not record accidents during both the before and the after period were left out of the analysis. The problem of zero counts is frequently encountered in epidemiology, where the convention of adding 0.5 has been adopted in order to solve the problem. Information given in the study shows that there is likely to be a regression-to-the-mean bias in the study.

Table 8 shows the estimated safety effects of porous asphalt when corrected for general accident trends on French motorways.

Table 8: Main results from study evaluating the effects on road safety of porous asphalt on French motorways. Taken from Brailly 1998.

Weather or road surface conditions	**Total number of injury accidents**	**Estimate of effect**	**Uniform effect on all sections**
Dry road	1586	+26 %	No
Wet road	306	-28 %	Yes
Normal weather	1695	+23 %	No
Bad weather	197	-31 %	Yes
All conditions	1903	+17 %	No

Source: TØI report 680/2003

In bad weather or in case of wet road surfaces, the results show a 25-30% decrease in injury accidents. On dry roads or in good weather, there is an increase of 23-26% in the number of accidents. The total safety effect has been estimated to a 17% increase in accidents.

The study scores 1 for specification of road surface conditions, 1 for specification of accident severity, 1 for control for confounding factors (controls for long term trends, but not for regression-to-the-mean), and 0 for statistical analysis. An inappropriate technique was used for the analysis, and a re-analysis is not feasible. Overall score for study quality is 0.45 on the 0 to 1 scale.

4.5 Bendtsen, Ellebjerg Larsen and Greibe 2002

This very extensive study covers a wide range of impacts of low noise road surfaces, in particular porous asphalt. A city street in Copenhagen was treated with porous asphalt and various impacts were measured. As far as road safety is concerned, the study relies on a very small sample. Only 2 accidents were recorded before treatment (1995-1998) and 2 after treatment (2000-2001). These numbers are far too small to make meaningful statements about impacts on road safety. Due to the very small sample size of this study, it has not been included in the meta-analysis reported in Chapter 6, nor has it been scored for study quality.

4.6 Commandeur et al 2002

This report is an analysis of the effects on road safety of various design elements and traffic control systems on Dutch motorways. The report includes a table giving accident rates for motorways with dense asphalt and motorways with porous asphalt for the years 1996, 1997 and 1998. An excerpt of information from this table is reproduced below as Table 9.

Table 9: Comparison of accident rates on Dutch motorways with dense or porous asphalt. Taken from Commandeur 2002

Year	Accidents and accident rate	Dense asphalt	Porous asphalt	Accident rate ratio
1996	Accidents	185	125	
	Accidents per million vehicle km	0.054	0.041	0.759
1997	Accidents	143	132	
	Accidents per million vehicle km	0.047	0.035	0.745
1998	Accidents	160	194	
	Accidents per million vehicle km	0.065	0.044	0.677

Source: TØI report 680/2003

Three comparisons are made. All three indicate a lower accident rate for porous asphalt than for dense asphalt. The accident rates apply to injury accidents, presumably both on dry and wet road surfaces. All roads had two lanes and a speed limit of 100 km/h.

The study is scored 0 for specification of road surface condition, 1 for specification of accident severity, 1 for control for confounding factors (controls for overall traffic volume and year) and 2 for statistical analysis. Overall score is 0.55 on the scale ranging from 0 to 1.

4.7 Sliwa 2003 – unpublished data

Data have been provided by the Bundesanstalt für Strassenwesen regarding sections of motorways in Germany that have either porous asphalt or dense asphalt. Based on these data, the comparison given in Table 7 can be made.

Table 10: Comparison of accident rates on motorways in Germany with dense or porous asphalt. Derived from spreadsheet forwarded by Nina Sliwa, BASt (unpublished data)

Data	Dense asphalt	Porous asphalt	Accident rate ratio
Accidents in total	332	742	
Accidents on dry road	234	531	
Accidents on wet road	98	211	
Million km of travel	2356.8	3290.3	
Accident rate	0.141	0.226	1.603
Dry road rate	0.099	0.161	1.626
Wet road rate	0.042	0.064	1.524

Source: TØI report 680/2003

The accident rate is higher for porous asphalt than for dense asphalt. This applies both to a dry road surface and to a wet road surface. Accident data refer to injury accidents and accidents resulting in major property damage.

The study is given a score of 1 for specification of road surface conditions, 0 for specification of accident severity, 1 for control for confounding factors (the sections appear to be along the same road, which implies that at least basic highway design parameters are similar for sections with dense and porous asphalt), and 2 for statistical analysis. Total score is 0.45 on 0 to 1 scale.

4.8 Summary of evidence from evaluation studies

Table 12 summarises the evidence on the effects of porous road surfaces or Italgrip extracted from the studies presented above. The table lists only studies that have been included in the meta-analysis presented in Chapter 6.

Table 11: Summary of estimates of effect of porous asphalt on road traffic accidents extracted from studies reviewed above

Study	Accident severity	Road surface condition	Estimate of effect (percent)
Tromp 1993	Not specified	Dry (2 lane)	+10
		Wet (2 lane)	+54
		Dry (multi lane)	–9
		Wet (multi lane)	–28
		Dry (matched pairs)	+1
		Wet (matched pairs)	+33
	Injury Accidents	All (2 lane)	–22
		All (multi lane)	+13
Herbst and Holzhammer 1995	Injury accidents	Dry	–64
		Wet	–50
Bonnot 1997	Not specified	All	–2
Brailly 1998	Injury accidents	Dry	+26
		Wet	–28
Commandeur et al 2002	Injury accidents	All (1996)	–24
		All (1997)	–25
		All (1998)	–32
Sliwa 2003	Not specified	Dry	+63
		Wet	+52

Source: TØI report 680/2003

Estimates of effect are seen to vary enormously. The large spread observed in estimates of effect is so great that it seems doubtful if synthesizing these estimates by means of meta-analysis makes much sense. An attempt has nevertheless been made and is reported in chapter 6.

5 Systematic review of studies: effects on risk factors

5.1 Relevant risk factors

A number of risk factors may be affected by the use of porous asphalt. The reason for this is the open structure of porous asphalt (with 20-25% air filled pores), which leads to:

- A reduction of traffic noise.
- Drainage of water from the road surface into the voids.
- Drainage of de-icing materials spread on the porous asphalt into the voids.
- A reduction of thermal conductivity.

In this chapter, studies that have evaluated the effects of porous road surfaces on risk factors will be reviewed.

5.2 Traffic noise

Since porous asphalt reduces traffic noise, it has been claimed that drivers tend to go faster on porous asphalt sections compared to dense asphalt sections because internal noise would also be reduced. However, such an effect has not been documented. Traffic noise measurements inside vehicles in Denmark (Bendtsen et al 2002) show no differences when driving on porous asphalt compared to dense asphalt, even though the outside traffic noise is reduced. The measurements were conducted when driving in urban areas at approximately 50 km/h. The behaviour of drivers should therefore not be affected by reduced outside noise. On the other hand, renewing road surfaces has in general been found to be associated with increased speed (see below). This behavioural adaptation is probably not related primarily to inside noise, but to the fact that a new surface is usually more even than an old and therefore more comfortable to drive on.

It is reasonable to assume that pedestrians and cyclists to some extent use their sense of hearing to locate motor vehicles. One could fear, that a 3-5 dB noise reduction from motor vehicles on porous asphalt would make it more difficult for pedestrians and cyclists to hear and identify motor vehicles. No literature has dealt with this safety issue.

5.3 Splash and spray – visibility in wet weather

The effect of porous asphalt on splash and spray has been evaluated by Nicholls and Daines (1992) and Nicholls (1997). In order to quantify the spray generated by vehicles on wet road surfaces, the obscuration caused by spray behind a moving vehicle was measured on porous asphalt and dense asphalt road sections. The results show that the spray on newly laid porous asphalt is less than 5% of that produced on a dense asphalt surface, which means that spray is reduced by more than 95%. The observed effect has remained for a number of years, even though it seems to be decreasing over time. The reduction in splash and spray will increase the visibility in wet weather, and reduce the likelihood of aquaplaning. Figure 1 illustrates a truck on a road section with and without porous asphalt.

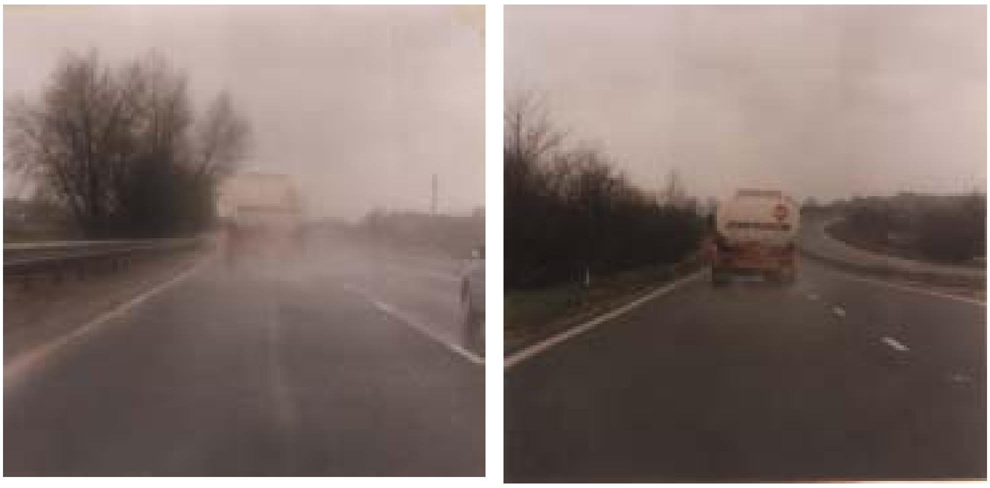


Figure 1. Examples illustrating splash and spray from a truck driving on dense and porous asphalt respectively. Taken from Nicholls, 1997

It is concluded that visual obstruction caused by splash and spray and the risk of aquaplaning caused by water on the road surface are strongly reduced by porous asphalt.

5.4 Friction – stopping distance

Delanne et al (1991) evaluated skid resistance and stopping distances on porous asphalt compared to dense asphalt. No differences in stopping distances were found between the two types of asphalt.

New asphalt has lower skid resistance values when braking with blocked wheels. The reason for this is a thin bitumen layer (skin) at the top, which is worn away by traffic until the aggregates are exposed. The wearing away usually takes up to 6 months. Since the bitumen layer tends to be thicker on porous asphalt and as there is less contact between tyre and road surface compared to dense asphalt concrete, newly laid porous asphalt can become more slippery than newly laid dense asphalt. When braking hard, the bitumen layer melts and becomes slippery, which leads to breaking distances that are 20-40% longer than on dense asphalt. (PIARC, 1995). The bitumen layer is worn away after 3-6 months (longer when modified bitumen is used). In order to warn drivers of this phenomenon, signs warning of slippery roads have been used. When braking without blocking the wheels (e.g. when using ABS) the braking distance on new porous asphalt is similar to dense asphalt, or even shorter. However, Nicholls (1997) mentions that U.K. studies show that the sideways-force coefficient 3 weeks after opening for porous asphalt road sections was the same as for dense asphalt. The two types of road sections had the same traffic volume. After 3 months the porous asphalt had higher sideways-force coefficients.

Bonnot (1997) describes skidding resistance on porous asphalt in the following terms: "In early life, porous asphalt has only mediocre skidding resistance at all speeds as a result of the thick layer of binder which coats the chippings, which in addition form a flat surface as a result of compaction. … Traffic removes this film of binder, a process which is accelerated by high traffic levels and which takes place more quickly in the case of a pure bitumen (it takes between 3 and 6 months with a pure bitumen and between 8 and 18 months with a modified binder)."

When porous asphalt replaces a worn road surface that has a low friction level, porous asphalt is likely to provide better friction, at least when the binder film has been worn off. It is concluded that porous asphalt performs at least as good as dense asphalt in terms of friction.

5.5 Rutting – evenness

Roads with potholes, very uneven surfaces or rutting can be a safety problem. Rutting is normally caused by heavy traffic and on dense asphalt rutting will increase the risk of aquaplaning since water is prevented from being drained off. Severe rutting might also influence driver behaviour e.g. when changing lanes. Unexpected unevenness or roughness can lead to dangerous situations and manoeuvres or even loss of control of the vehicle. However, studies (Elvik and Vaa 2003) indicate that repairing or resurfacing roads can lead to more accidents, probably as a result of higher speed and less driver attention.

Porous asphalt is in general much more resistant towards rutting than dense asphalt concrete. The deformation rates measured in the UK show a 2mm deformation initially and less than 0.5 mm per year on average after 8 years (Nicholls, 1997). Those road sections with the highest binder contents tended to show the greatest deformations, but the highest rates of deformation were still acceptable.

When a porous asphalt road section is nearly worn out (after 8-12 years) the observed deterioration is typically ravelling. Even though the ravelling process can start very suddenly and continue rapidly, it will only in very severe situations affect road safety.

It is concluded that porous asphalt performs better than dense asphalt in terms of rutting and evenness.

5.6 Light reflection

Nicholls (1997) concludes that subjective impressions, supported by photos, have indicated that reflections of light from oncoming vehicles or street lighting are reduced on wet porous asphalt compared to wet dense asphalt concrete. The reason for this is that porous asphalt does not hold a thin layer of water to reflect the light. Road markings, etc., are therefore more visible. It has also been found that porous asphalt will reflect the light differently from dense asphalt, even during dry road conditions.

It is concluded that porous asphalt improves visibility conditions, by reducing discomfort glare caused by light reflecting from water ponds or a wet road surface.

5.7 Performance in wintertime

The performance of porous asphalt during winter is described by Bonnot (1997), Nicholls (1997) and Norrts (1996).

The behaviour of porous asphalt during winter differs from ordinary dense asphalt concrete due to the open structure, which leads to:

- Drainage of de-icing materials from the road surface
- A reduction of thermal conductivity
- The possibility of water being transported between voids

5.7.1 Salt on road surface

On road sections of dense asphalt concrete, the salt mixes with the moisture on the surface. Since porous asphalt contains more moisture and because salt disappears into the voids, the amount of salt needed is considerably higher on porous asphalt. An increased salt consumption of 25-100% must be expected.

On porous asphalt, the air pumping effect from tyres of passing vehicles will mix the salt with the moisture in the voids and continuously circulate the salt solution from the voids and to the surface – and vice versa. The air pumping effect will, as long as the traffic density is high, keep the road surface clean from snow. In general, a driver does not notice any difference between porous asphalt and dense asphalt concrete as long as there is sufficient traffic on the road.

If the road surface is dry when salt is spread, the salt will be crystallised on the surface, which on dense asphalt concrete can be seen as a whitening of the road surface as the salt dries. The salt will subsequently disappear, worn off by traffic. On porous asphalt the salt will stay longer since it crystallises in the voids.

Since the behaviour of salt on porous asphalt surfaces is so different from dense asphalt, locally adjusted salt spreading strategies are required.

5.7.2 Road surface temperature

Due to the lower thermal conductivity of porous asphalt, the road surface temperature drops below the freezing point earlier than on dense asphalt concrete. The temperature also stays below the freezing point longer if the air temperature rises above the freezing point, especially if the air temperature is close to the freezing point.

5.7.3 Humidity behaviour

The open structure of porous asphalt makes the evaporation very low and the voids in the porous asphalt contain humidity for a long time. Remaining moisture in the voids combined with lower road surface temperatures suggest that porous asphalt is more sensitive to freezing on wet road sections. A good ice warning system will therefore be needed for road sections with porous asphalt. Bonnot (1997) shows statistics from French motorways indicating that the road surface was covered by ice 1-6% of the time on porous asphalt, compared to only 0.5-1% of the time on dense asphalt.

5.7.4 Freezing rain

In freezing rain, the behaviour of porous asphalt and dense asphalt concrete differ considerably. Black ice is caused by freezing rain, as the rain freezes on contact with the road surface. Salt on the road surface will in the beginning melt the freezing rain but the amount of salt will soon decrease as it disappears into the voids. During snowfall the salt in the voids and on the road surface will be mixed due to the air-pumping effect, but in freezing rain this phenomenon is not seen, because the ice on the road surface stops the circulation of salt between voids and road surface.

The overall conclusion is that porous asphalt is more prone to be covered by ice in winter than dense asphalt. This effect can, however, be counteracted by spreading more salt on porous asphalt than on dense asphalt.

5.8 Speed

A British study has measured speed on road sections with porous and dense asphalt during wet and dry periods (Nicholls and Daines, 1992). Cars appear to reduce speed in wet weather by 10 km/h on dense asphalt (from 126 to 116 km/h). The corresponding reduction on porous asphalt was 7 km/h (124 to 117 km/h). Since the road sections with porous asphalt were relatively short, giving the driver little time to get used to better visibility, the changes in speed for porous asphalt might be conservative, that is when drivers become accustomed to the higher visibility on porous asphalt, they will reduce their speed even less than observed in this study. The result is based on only 200 vehicles for each category of dense asphalt (dry/wet) and porous (dry/wet) situations respectively.

Edwards (2002) examined motorists' speed in wet weather compared to dry weather on two different kinds of road surfaces, porous asphalt and conventional dense asphalt. The roads that were compared were motorways close to Cardiff and Bristol. The following mean speeds were observed during fine weather and rain:

Fine weather, dense asphalt:	103 km/h
Rainy weather, dense asphalt:	99 km/h
Fine weather, porous asphalt:	113 km/h
Rainy weather, porous asphalt:	109 km/h

Mean speeds were higher on porous asphalt than on dense asphalt, both in fine weather and in rain. However, the road sections have different traffic loads and number of lanes and the speed levels can therefore not be compared directly.

A 4 km/h reduction in speed during rainy weather was observed for both porous and dense asphalt. This reduction was, however, insufficient to maintain the same stopping distance in rainy weather as in fine weather.

A Danish study (Bendtsen et al 2002) measured speed before and after opening a new urban road section with porous asphalt. No significant changes in speed where found. It should be mentioned though, that the length of the road section is only 400m and the speed measurements were based on only a few days of traffic in the before and after period, mainly in dry weather.

Some studies (e.g. Swart, 1997) have pointed out that traffic capacity of porous asphalt is higher than of dense asphalt. The most likely reason is higher speed and shorter headways during rainy conditions. However, no studies have confirmed changes in capacity.

It is concluded that drivers tend to adapt their speed less to rainy weather on porous road surfaces than in dense road surfaces. This is an adverse effect of porous asphalt for road safety. Higher speed and capacity are, however, advantageous for mobility, as long as the number of accidents does not increase. Accidents are often associated with significant traffic delays, in particular on motorways.

5.9 The need for more frequent resurfacing

A literature review (Elvik and Vaa 2003) indicates that resurfacing roads is associated with a small increase in the number of accidents (3-6%). Another study (Leden et al, 1998) based on road sections with dense asphalt concrete show that new asphalt pavements gives higher speeds and more accidents (+7%) within the first years, and road sections with "good" pavements have higher accident rates compared with "less good" pavements. These results refer to ordinary resurfacing of roads.

It must be expected that new pavements (porous as well as dense asphalt concrete) will produce higher speed initially due to smoother and more comfortable surfaces. This must be kept in mind when evaluating the safety effects of pavements.

The need for more frequent resurfacing when porous asphalt is applied is thus an adverse effect for road safety.

5.10 Overall assessment of effects on risk factors

Ragnøy (1989) has assessed the combined effects of porous asphalt in terms of aquaplaning, splash and spray, wet road surface friction and light reflection. He concludes that porous asphalt influences all these risk factors favourably. A potential reduction of wet weather accidents of 9.5% in daytime and 13.6% at night was estimated. These estimates were based on the assumption that there are no adverse effects of porous asphalt, for example in terms of higher speed. In Table 12, an attempt has been made to summarise current evidence on the effects of porous asphalt on various risk factors.

Porous asphalt has a favourable impact on splash and spray, on the risk of aquaplaning, on rutting and evenness, and on light reflection from vehicle headlights and the road surface. There is no effect, or a negligible effect, on driver behaviour related to traffic noise and stopping distance on dry or wet road surfaces. Performance in wintertime, driving speed and the frequency of resurfacing are all adversely affected by porous asphalt.

Table 12: Summary of effects of porous asphalt on various risk factors

Risk factors affected	**Effect of porous asphalt**
Driver behaviour induced by changes in traffic noise	No effect
Splash and spray - visibility in wet weather	Favourable
Risk of aquaplaning	Favourable
Friction – stopping distance	No effect
Rutting – evenness	Favourable
Light reflection	Favourable
Performance in wintertime	Adverse
Speed	Adverse
Need for more frequent resurfacing	Adverse

Source: TØI report 680/2003

The net effect of these various impacts on risk factors is difficult to assess. It depends on the relative strengths of the various effects. If, for example, there is a modest effect on driving speed, the favourable effects on other risk factors may lead to a net gain in road safety. If, on the other hand, there are large increases in speed, and the first winter is long and severe, the net effect may be adverse. The fact that the effects on risk factors are so mixed and complex makes it impossible to predict the net result of the impacts on risk factors in terms of changes in the number of accidents. In a sense, this confirms the evidence from studies that have evaluated the effects on accidents, since these studies show highly varying effects, that on the average appear to be fairly close to zero (i.e. no change in road safety).

6 Synthesis of evidence: meta-analysis

6.1 Exploratory analysis – effect on accidents

A total of 18 estimates of the effect on accidents of porous asphalt were presented in Table 11. These estimates ranged from an accident reduction of 64% to an increase of 63% in the expected number of accidents. Eight out of eighteen estimates of effect indicated an increase in accident rate; ten out the twenty estimates of effect indicated a reduction in accident rate. Does it make sense to combine these highly heterogeneous estimates of effect into an overall estimate?

An exploratory meta-analysis has been performed in order to answer this question. To do this analysis, the first step was to estimate the statistical weight to be assigned to each estimate of effect. For most of the estimates of effect, a statistical weight was assigned on the basis of the number of accidents serving as the basis for the estimation of accident rates and accident rate ratios. Thus, for example, the first estimate of effect in Tromp's study (Tromp 1993) was based on 2876 accidents on dense asphalt and 231 accidents on porous asphalt. The statistical weight assigned to the estimate of effect based on these accident figures is:

Statistical weight = 1/(1/2876 + 1/231) = 213.83

This is the inverse variance weight for a fixed effects model of meta-analysis, which weights estimates of effect on the basis of the sampling variance of each estimate. Strictly speaking, the statistical weight of an accident rate ratio should take sampling variance in exposure (vehicle km of driving) into account as well. However, no meaningful estimate of this sampling variance is available; hence it has been disregarded.

The study of Herbst and Holzhammer (1995) does not state the number of accidents, but gives accident rates for dry, wet and wintry surface conditions. A rough approximate estimate of the statistical weights to be given to the two estimates of effect derived from this study can nevertheless be obtained. The annual observed dry road accident rates (injury accidents per million vehicle kilometres) during the before period were 0.14, 0.31, 0.15, 0.17 and 0.32. The fairly large variation in accident rates from year to year indicates that the number of accidents serving as the basis for these accident rates is rather small. The variance of the five estimates is 0.008. The inverse of this variance is 125. This is taken as the statistical weight of the estimate of effect for dry roads in Herbst and Holzhammer's study. The mean accident rate during the before period for wet roads was 0.06, compared to 0.22 for dry roads. It is not clear how the estimate was obtained, but the fact that it is lower than the estimate for dry roads indicates that the number of wet road accidents has simply been divided by total exposure, and not by exposure during wet weather, which may have been unknown. Hence, the statistical weight given to the estimate of effect for wet roads was estimated as (0.06/0.22) x 125, in which 0.06/0.22 is the ratio of wet to dry mean accident rate in the before period, and 125 is the statistical weight assigned to the estimate of effect for dry roads.

Bonnot (1997) gives two accident rates for French motorways. One applies to 555 km of motorway with porous asphalt, the other applies to 2541 km of motorway with dense asphalt. The number of accidents is not stated. According to the IRTAD database, the total length of motorways in France in 2001 was 9632 kilometres. The number of fatalities was 534. The fatality rate was 4.8 per billion vehicle kilometres of driving. Based on these numbers, the annual amount of driving on French motorways can be estimated to 111,250 million vehicle kilometres. Assuming that the sample of motorways quoted by Bonnot is representative, annual exposure on these motorways can be estimated to (555/9632) x 111,250 = 6410.3 million vehicle kilometres of travel for motorways with porous asphalt and to (2541/9632) x 111,250 = 29,348.7 million vehicle kilometres of travel for motorways with dense asphalt. Bonnot states that the accident rate was 32.3 per 100 million vehicle kilometres for motorways with porous asphalt, and 33.0 per 100 million vehicle kilometres for motorways with dense asphalt. The annual number of accidents can then be estimated to 2071 for motorways with porous asphalt and 9685 for motorways with dense asphalt. These numbers have been used to assign a statistical weight to Bonnot's study.

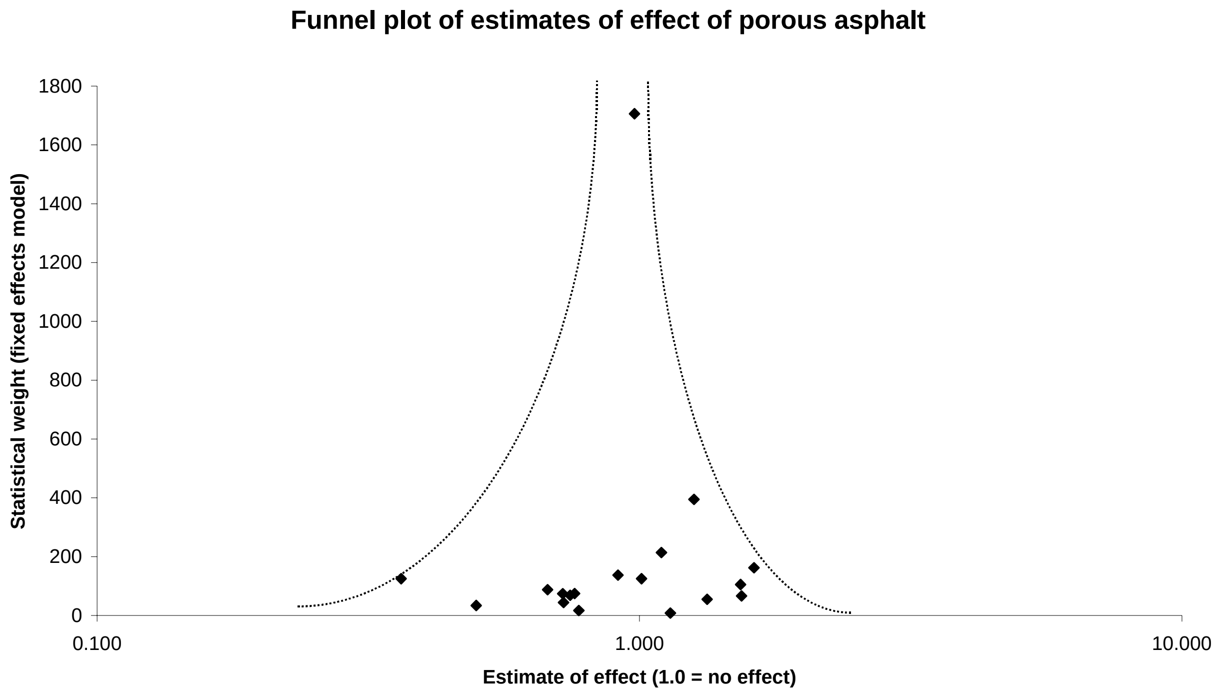
One way of assessing whether it makes sense to synthesise a set of estimates of effect, is to prepare a funnel plot of these estimates. In such a plot, each estimate of effect is plotted on the horizontal axis and the statistical weight of the estimate on the vertical axis. The underlying idea is that estimates of effect based on large samples are more precise than those based on small samples and should therefore vary less. If this is found to be the case, and if the plot is symmetrical around the weighted mean estimate of effect, synthesising estimates of effect in the form of a weighted mean estimate makes sense. Figure 2 presents a funnel plot of estimates of the effect on accidents of porous asphalt.

A single estimate of effect on top of the diagram is based on a much larger statistical weight than all the other estimates. This estimate is from Bonnot's study. However, even if this particular estimate of effect is disregarded, a tendency can be seen for estimates based on large samples to vary less than estimates based on small samples. The preliminary conclusion is that the scatter of data points in the funnel plot is sufficiently well-behaved that it makes sense to try to summarise evidence by means of a meta-analysis.

6.2 Meta-analysis of studies evaluating effects on accidents

There are two basic models of meta-analysis: the fixed effects model and the random-effects model. The fixed effects model is based on the assumption that the variation in estimates of effect observed in a set of studies is random only, that is it reflects sampling variation only. The validity of making this assumption can be tested statistically. If the test statistic is significant, there is systematic variation in estimates of effect. A random effects model of meta-analysis is then adopted, in which the statistical weight assigned to each estimate of effect is modified by adding a variance component, reflecting the between-study variation in estimates of effect. For a technical description, see e. g. Fleiss (1993), Shadish and Haddock (1994), and Elvik and Vaa (2003).

Table 13 presents summary estimates of effect based on various approaches to meta-analysis, starting from the most liberal and moving to the most conservative. There are 6 estimates of effect for dry roads, 6 estimates of effect for wet roads, 6 estimates of effect for which road surface condition was not stated. In total there are 18 estimates of effect.



Source: TØI report 680/2003

Figure 2: Funnel plot of estimates of effect on accidents of porous asphalt

Table 13: Summary estimates of effects on accidents of porous asphalt

		Percent change in the number of accidents	
Model of analysis	**Road surface**	**Best estimate**	**95% CI**
Fixed effects	Dry	+5	(–1, +11)
	Wet	+8	(–3, +19)
	Not stated	–6	(–10, –1)
	All	–1	(–4, +2)
Random effects	Dry	–4	(–33, +37)
	Wet	–2	(–32, +41)
	Not stated	–19	(–32, –2)
	All	–14	(–26, +0)
Random effects, adjusted for study quality	Dry	+3	(–39, +72)
	Wet	+5	(–37, +77)
	Not stated	–23	(–42, +2)
	All	–14	(–31, +8)
Simple mean	Dry	+5	(–2, +11)
	Wet	+6	(–5, +16)
	Not stated	–15	(–28, –2)
	All	–2	(–8, +5)

Source: TØI report 680/2003

The fixed effects analysis shows very small changes in the number of accidents. All summary estimates indicate changes of less than 10%. Only one of the estimates are statistically significant. That is the estimate of effect referring to unspecified road surface conditions. It is surprising that the summary estimates of effect indicate a small increase in the number of accidents both for dry and wet road surfaces. However, these summary estimates are not statistically significant.

Analysis found that individual estimates of effect were heterogeneous. A random effects analysis was therefore performed. The results of the random effects analysis differed from the fixed effects analysis, in that all summary estimates of effect now indicate a reduction in the number of accidents. Only one of the summary estimates of effect based on the random effects model is statistically significant at the 5% level.

The random effects model was carried one step further by adjusting for study quality. This was done simply by multiplying statistical weights by quality score:

Quality adjusted analysis = Random effects weights x Quality score

Summary estimates of effect adjusted for study quality are mixed, but the overall estimate, based on all 18 individual estimates of effect again points towards a reduction of the number of accidents. The summary estimates are, however, quite far from statistical significance.

Finally, a simple mean of individual estimates of effect has been computed. The simple mean estimates are all close to zero effect and are all far from statistical significance at conventional levels.

Based on this analysis, it is concluded that the summary estimates of the effects on road safety of porous asphalt do not display a very clear or consistent pattern. Few estimates are statistically significant, and most summary estimates are close to zero, indicating no change in road safety. It is concluded that no clear effect on road safety of porous asphalt can be found.

6.3 Meta-analysis of studies evaluating effects on risk factors

A meta-analysis of studies that have evaluated the effects of porous asphalt on various risk factors has not been attempted, as the number of studies that have evaluated these effects is rather small, and study findings have not always been presented in a way that easily lends itself to inclusion in a meta-analysis.

7 Other road surface treatments influencing road safety and traffic noise

7.1 Is there a trade-off between different chacteristics of road surfaces ?

Road surfaces should ideally speaking satisfy a number of requirements. The most important of these include the following:

- Durability: A good road surface should last long and be resistant to wear and tear.
- Skid resistance: A good road surface should provide good skid resistance and thus a high level of road safety.
- Light reflection: A good road surface should adequately reflect light without causing discomfort glare.
- Tyre and vehicle wear: A good road surface should not cause damage to tyres or cars or greatly speed up normal wear and tear.
- Rolling resistance: A good road surface should not unduly increase rolling resistance, thus leading to increased fuel consumption.
- Traffic noise: A good road surface should minimise traffic noise (due to tyre/road interaction).

An ideal road surface would have all these characteristics. In practice, however, the requirements for an ideal road surface may sometimes conflict, making it necessary to sacrifice one of the desirable characteristics in order to get more of another of the desirable characteristics. This chapter will discuss the following question:

To what extent is it necessary to make a trade-off between noise performance and safety performance for various types of road surfaces and car tyres?

Safety performance is best described in terms of the accident rate (number of accidents per million vehicle kilometres of travel). In many studies skid resistance, as measured by the friction coefficient, is used as an indicator of safety. It is known, however, that drivers tend to adapt their behaviour, in particular speed, the road surface friction. Hence it is not obvious that improving skid resistance (road surface friction) will always improve safety. The first question that must be answered is whether or not improving skid resistance is associated with a reduction of the number of accidents. If this is found to be the case, then skid resistance is a valid indicator of road safety.

7.2 The relationship between skid resistance and the number of accidents

Elvik et al (2003) have reviewed studies that have evaluated the effects on the number of accidents of improving road surface friction. Table 14 summarises the results of this review.

Improving the skid resistance of a road surface is consistently found to reduce the number of accidents occurring on a wet road surface. At low initial levels of skid resistance (friction coefficient below 0.50), a large improvement in skid resistance is associated with a larger accident reduction than a small improvement in skid resistance. The results presented in Table 14 clearly indicate that skid resistance affects road safety, and show that by improving skid resistance, one may expect the number of accidents to be reduced. It is therefore concluded that skid resistance is a valid indicator of road safety.

Table 14: Results of meta-analysis of studies that have evaluated the effect on accidents of improving road surface skid resistance. Based on Elvik et al 2003

		Percentage change of the number of accidents	
Accident severity	Types of accident influenced	Best estimate	95% confidence interval
Increasing friction by 0.05 units from an initial level of less than 0.50			
Not specified	Accidents on wet road surface	-35	(-52, -12)
	Accidents on dry road surface	-1	(-18, +20)
	All accidents	-10	(-25, +7)
Increasing friction by 0.10 units from an initial level of less than 0.50			
Not specified	Accidents on wet road surface	-42	(-61, -14)
	Accidents on dry road surface	-10	(-22, +5)
	All accidents	-17	(-31, +1)
Increasing friction by 0.25 units from an initial level of less than 0.50			
Not specified	Accidents on wet road surface	-56	(-71, -35)
	Accidents on dry road surface	-12	(-25, +4)
	All accidents	-32	(-40, -22)
Increasing friction by about 0.10 units from an initial level of 0.50-0.60			
Not specified	Accidents on wet road surface	-40	(-51, -26)
	Accidents on dry road surface	-4	(-13, +5)
	All accidents	-11	(-21, -1)
Increasing friction by 0.10 units from an initial level of more than 0.60			
Not specified	Accidents on wet road surface	-32	(-53, +1)
	Accidents on dry road surface	-26	(-44, -1)
	All accidents	-26	(-45, +1)

Source: TØI report 680/2003

The following discussion will proceed on the assumption that high skid resistance indicates high road safety. The following topics will be covered:

- The relationship between car tyre friction and noise
- The optimising of road surface characteristics in general
- Surface treatment of concrete road surfaces
- The Italgrip road surface treatment

7.3 The relationship between car tyre friction and noise

Sandberg and Ejsmont (2002) review a number of studies that have evaluated the relationship between car tyre friction and noise emission. Based on these studies, they conclude that: “no significant trade-off in safety (friction) seems to be necessary when designing low noise tyres of today” (page 396).

7.4 Optimising road surface characteristics

Descornet (1989) discusses the optimisation of road surface characteristics in general. A road surface can be described in terms of microtexture, macrotexture, megatexture and roughness. Each of these inherent characteristics of a road surface can be described in terms of its wavelength. For microtexture and macrotexture there exists an optimal range for the wavelength. Road surfaces whose microtexture and macrotexture have the optimal wavelength will have many of the desirable characteristics mentioned in section 7.1. Megatexture and roughness, on the other hand are to be avoided, as these characteristics can adversely affect riding comfort, vehicle wear and road holding. Descornet concludes that road surfaces that have optimal wavelengths for microtexture and macrotexture will normally perform well in terms of skid resistance, splash and spray, light reflection and outside noise. Hence, for an optimally designed road surface, there is, in general, no trade-off between skid resistance and traffic noise.

7.5 Surface treatment of concrete road surfaces

Concrete road surfaces tend to be used because of their great durability. A concrete road surface is, however, dense and will not drain water very effectively. If treated by means of grooving, a concrete road surface will usually improve its performance in terms of water drainage and splash and spray. Pavement grooving will, on the other hand, adversely affect traffic noise. Research has therefore been performed in order to develop surface treatments for concrete pavements that will both improve skid resistance, water drainage and traffic noise.

Descornet, Fuchs and Buys (1993) report on the results of this research. It is concluded that it is possible to apply surface treatments to concrete road surfaces that will both improve skid resistance and reduce noise. A subsequent study (Descornet et al 2000) found that there is no relationship between sideway force coefficient (a measure of skid resistance) and noise level.

7.6 The Italgrip system - Spinoglio 2003 - unpublished data

Italgrip is a surface treatment that is applied mainly to improve skid resistance. According to data forwarded by Silvio Spinoglio, manager of Italgrip, application of Italgrip has improved road surface friction (friction coefficient) from values in the range of 0.30 to 0.45 before treatment to values in the range of 0.50 to 0.75 after treatment. The initial effect on skid resistance of applying Italgrip can be quite large, improving friction by a value of 0.25 to 0.30. After some time, however, some of this initial effect is lost as Italgrip is worn away.

The following data regarding accidents at “Italgrip sites” (not further described) have been forwarded by Silvio Spinoglio (Table 15).

Table 15. Accidents before and after treatment with Italgrip for selected sites of motorways in Italy. Unpublished data forwarded by Silvio Spinoglio

	Recorded number of accidents for Italgrip sites								
	Years before				Years after				
Site	4	3	2	1	1	2	3	Mean before	Mean after
309s		15	19	22	9	9		18.7	9.0
248s		11	15	10	4	2		12.0	3.0
245n		17	17	13	12	12		15.7	12.0
356n			6	8	0	2		7.0	1.0
410n				6	0	3		6.0	1.5
123s		22	17	9	2	6	6	16.0	4.7
35w	10	11	7	11	0	2		9.8	1.0
41w	25	25	24	23	17	17		24.3	17.0
0w		15	17	11	6			14.3	6.0
236n		18	13	5	2	6		12.0	4.0
222n			9	10	2	2		9.5	2.0
223n		18	10	24	3	2		17.3	2.5
233s	25	6	5	18	6	1		13.5	3.5
313s		10	1	5	3	4		5.3	3.5
21n		18	26	17	10	11		20.3	10.5
22e		5	7	11	3			7.7	3.0

Source: TØI report 680/2003

Nothing is stated about accident severity, nor is it stated whether accident data refer to wet or dry road surfaces. The mean number of accidents per year for all sites combined was reduced from 209.3 to 84.2, a reduction of nearly 60%. To the extent that Italgrip has been applied at black spots, this estimate is likely to overstate the true effect. A simple way of controlling for regression-to-the-mean, proposed by Brüde and Larsson (1982), is to omit the year having the highest count of accidents from the before period and take the average of the remaining years. For site 309s, as an example, the count of 22 in the year before treatment is omitted. The average count for years 3 and 2 before is 17.0 [(15 + 19)/2], as opposed to 18.7 if year 1 before is included. This reduces the number of accidents in the before period from 209.3 to 182.0. The estimate of effect now becomes an accident reduction of 53.7%.

Despite the uncertainty of this estimate of effect, it is likely that Italgrip does reduce the number of accidents, since it greatly improves skid resistance. According to information forwarded by Italgrip, its application favourably affects most of the risk factors discussed in chapter 5. However, this has not been confirmed by independent research.

7.7 Conclusions

Based on the studies reviewed in this chapter, it is concluded that there is, in general, no conflict between providing good skid resistance and low noise. Several types of road surface treatments have been developed that will both improve skid resistance and reduce traffic noise. Hence, there are alternatives to porous asphalt in regard to the objectives of improving road safety and abating traffic noise.

8 Discussion and conclusions

8.1 Ways of interpreting available knowledge

A distinction is sometimes made between two ways of interpreting the results of research: (1) Methodological, and (2) Substantive. A methodological interpretation of research usually criticises the research by pointing out flaws in research methods. In this report, the methodological point of view is represented by the quality assessment made of studies that have evaluated the effects on accidents of porous road surfaces. A formal quality scoring system has been used. According to this system, studies should be treated with caution if they score low for quality. An ideal study scores 1 for quality, a study whose results have very limited applicability scores 0. Ideally speaking, we would of course like all studies to score 1 for quality, thus ruling out methodological criticism of the studies.

The mean quality score assigned to studies included in this review was 0.49. The best study scored 0.70, the worst scored 0.10. This means that all studies are subject to relevant criticism from a methodological point of view. Porous asphalt appears to have been badly served by research: Many of the studies that have been made to evaluate the effects of porous asphalt are poorly designed and have been poorly reported, with respect to observing important criteria for high-quality road safety evaluation studies. An adjustment for study quality was made as part of the meta-analysis of studies that have evaluated the effects on accidents of porous asphalt. This adjustment did not greatly affect summary estimates of effect, but did increase the uncertainty of these estimates.

A substantive interpretation of research usually explains the findings of research in terms of known causal mechanisms or processes. In this report, the substantive point of view is represented by the evaluation of effects of porous asphalt on risk factors, in addition to effects on accidents. In the best of all possible worlds, one would find clear and consistent effects of porous asphalt on various risk factors that would explain the effects of the measure on accidents. One could, for example, find that splash and spray are greatly reduced, aquaplaning no longer occurs, visibility at night is improved, and drivers do not speed up. If this had been found, and if the number of accidents in wet weather had been reduced, the causal chain of impacts on risk factors and accidents would make sense and lend credibility to the findings of research.

Unfortunately, we do not live in the best of all possible worlds. The effects of porous asphalt on various risk factors are inconsistent and highly uncertain. Few studies have evaluated these effects. Each study has usually evaluated effects on just one or two of the relevant risk factors, and not on the whole set of these factors. Effects on various risk factors go in different directions, and the net impact of porous asphalt on accidents cannot be predicted on the basis of its effects on single risk factors.

Basically, the main finding of this review is that the effects on road safety of porous asphalt are to a large extent unknown. While some studies have evaluated these effects, not all of these studies can be trusted and their findings are highly inconsistent. More research is needed in order to assess the effects on road safety of porous asphalt more precisely than is currently possible. Current knowledge does not enable us to answer the four research problems that were formulated in Chapter 1.

There are, however, alternatives to porous asphalt. In general, road surfaces and car tyres that provide good skid resistance, and thus a high level of road safety, are not associated with a higher level of noise than road surfaces or car tyres that provide less good skid resistance.

8.2 Summary and conclusions

This report contains a systematic review of studies that have evaluated the effects of porous asphalt on accidents and risk factors associated with accident occurrence. The main findings of the review can be summarised as follows:

1. A search has been made for studies that have evaluated the effects on road safety of porous asphalt. A total of eighteen estimates of the effects on accidents of porous asphalt have been found, derived from six studies. These estimates are highly inconsistent. Ten estimates indicate a reduction of the number of accidents. Eight estimates indicate an increase of the number of accidents.
2. Estimates of the effect on accidents of porous asphalt were summarised by means of a meta-analysis. This analysis was based on eighteen of the twenty estimates of effect retrieved. As part of this analysis, a critical assessment of study quality was made and a score for study quality developed. A meta-analysis was performed both by means of a fixed effects model, a random effects model, and a random effects model adjusting for study quality.
3. Summary estimates of effect in the meta-analysis were all close to zero, and few of the summary estimates of effect were statistically significant at conventional levels. Hence, no statistically significant effect on road safety of porous asphalt can be detected.
4. An attempt was made to bolster the estimate of safety effects of porous asphalt, by surveying studies of the effects of porous asphalt on various risk factors associated with accident occurrence. The survey was not able to locate very many studies that have evaluated effects of porous asphalt on risk factors. The studies that were reviewed have found inconsistent effects, which are difficult to interpret. Some risk factors appear to be favourably influenced by porous asphalt, other risk factors are adversely influenced. The effect of porous asphalt on accident cannot be predicted on the basis of effects on risk factors.

5. A small survey has been made of studies that discuss in general terms desirable characteristics of road surfaces, in particular whether there is trade-off between safety and noise abatement. It was found that these two characteristics of road surfaces can be successfully combined for a number of road surfaces, including concrete surfaces. In general, providing good skid resistance will improve road safety and will not adversely affect traffic noise. Good alternatives to porous asphalt do therefore exist.

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