Maintenance of paved roads
Current state of knowledge and need for research
Peter W Arnberg, Gunnar Carlsson, Lennart Djärf, Per-Gunnar Land, Georg Magnusson, Rein Schandersson, Bo Simonsson and Leif Wiman
Maintenance of paved roads

Current state of knowledge and need for research

Peter W Arnberg, Gunnar Carlsson, Lennart Djärf, Per-Gunnar Land, Georg Magnusson, Rein Schandersson, Bo Simonsson and Leif Wiman

VTI, Linköping 1985
Preface

Almost half of research resources of the Swedish Road and Traffic Research Institute (VTI) are utilized in projects which are more or less directly related to questions concerning road pavements, specially road surfacings.

Research in the Institute's Road Division is oriented towards roads and materials. In the Road User and Vehicle Division and the Traffic Division, research is aimed at analysing how various road surface properties influence vehicles, road users, traffic and the environment, and developing systems for this purpose.

The largest part of research is commissioned by the Swedish National Road Administration (VV), although a considerable part is financed with internal funds. Swedish National Road Administration projects are initiated and/or administered by its own divisions and the Institute's research projects are initiated by the respective division. However, it has long been known that there is a need for increased coordination of research into road surfacing questions within the VTI. It is important to make effective use of the multidisciplinary expertise of the VTI, which is perhaps the most important reason for the existence of a research institute of this type.

A working group was therefore set up at the VTI in April 1982 with representatives from the three research divisions. The group, which was headed by Gunnar Carlsson, was instructed to produce guidelines for coordinated research into road pavements. The results of the group's work were presented in November 1982 at a seminar at the VTI. Meddelande 406 documents the group's proposals.

In addition to the members of the working group (the authors of this VTI Meddelande) the participants included the following researchers at the VTI:

Urban Björketun       Evert Ohlsson
Rune Gandahl          Ulf Sandberg
Ulf Hammarström       Hans Sävenhed
Gabriel Helmers

VTI MEDDELANDE 406 A
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>1</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>1  AIMS OF THE WORKING GROUP</td>
<td>1</td>
</tr>
<tr>
<td>2  GENERAL BACKGROUND</td>
<td>3</td>
</tr>
<tr>
<td>3  AIMS IN MAINTENANCE OF PAVED ROADS</td>
<td>5</td>
</tr>
<tr>
<td>4  SYSTEMS FOR MAINTENANCE STRATEGIES</td>
<td>9</td>
</tr>
<tr>
<td>5  PAVEMENT PERFORMANCE</td>
<td>14</td>
</tr>
<tr>
<td>5.1 Surface wear</td>
<td>16</td>
</tr>
<tr>
<td>5.1.1 Wear from studded tyres</td>
<td>16</td>
</tr>
<tr>
<td>5.1.2 Other surface wear</td>
<td>18</td>
</tr>
<tr>
<td>5.2 Deformation in the bituminous pavement</td>
<td>18</td>
</tr>
<tr>
<td>5.2.1 Texture changes</td>
<td>19</td>
</tr>
<tr>
<td>5.2.2 Rutting through plastic deformation</td>
<td>19</td>
</tr>
<tr>
<td>5.3 Structural deterioration</td>
<td>20</td>
</tr>
<tr>
<td>5.3.1 Rutting through permanent (plastic) deformations in unbound courses including the subgrade</td>
<td>20</td>
</tr>
<tr>
<td>5.3.2 Cracks and alligator cracking</td>
<td>21</td>
</tr>
<tr>
<td>5.4 Frost and ground processes</td>
<td>22</td>
</tr>
<tr>
<td>5.5 Performance models</td>
<td>24</td>
</tr>
<tr>
<td>6  EFFECTS ON TRAFFIC OF PAVEMENT SURFACE CONDITION</td>
<td>28</td>
</tr>
<tr>
<td>6.1 Traffic safety - accidents and indirect measures of traffic safety</td>
<td>29</td>
</tr>
<tr>
<td>6.2 Journey time/transport facilities</td>
<td>31</td>
</tr>
<tr>
<td>6.3 Vehicle costs</td>
<td>32</td>
</tr>
<tr>
<td>6.3.1 Fuel consumption</td>
<td>33</td>
</tr>
<tr>
<td>6.3.2 Tyre wear</td>
<td>34</td>
</tr>
<tr>
<td>6.3.3 Vehicle wear</td>
<td>36</td>
</tr>
<tr>
<td>6.3.4 Damage to goods</td>
<td>38</td>
</tr>
<tr>
<td>6.4 Comfort and performance</td>
<td>39</td>
</tr>
</tbody>
</table>

VTI MEDDELANDE 406 A
<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>7 EXTERNAL EFFECTS OF PAVEMENT SURFACE CONDITION</td>
</tr>
<tr>
<td>42</td>
<td>8 MEASURING STRUCTURAL CONDITION</td>
</tr>
<tr>
<td>43</td>
<td>9 MEASURING ROAD SURFACE CONDITION</td>
</tr>
<tr>
<td>44</td>
<td>9.1 Roughness</td>
</tr>
<tr>
<td>45</td>
<td>9.2 Cross profile</td>
</tr>
<tr>
<td>46</td>
<td>9.3 Crossfall</td>
</tr>
<tr>
<td>48</td>
<td>9.4 Friction</td>
</tr>
<tr>
<td>49</td>
<td>9.5 Texture</td>
</tr>
<tr>
<td>50</td>
<td>9.6 Light reflection</td>
</tr>
<tr>
<td>53</td>
<td>10 TRAFFIC MEASUREMENT AND PROGNOSIS</td>
</tr>
<tr>
<td>53</td>
<td>10.1 Heavy traffic/axle loads</td>
</tr>
<tr>
<td>53</td>
<td>10.2 Studded tyres</td>
</tr>
<tr>
<td>55</td>
<td>11 EVALUATION OF EFFECTS</td>
</tr>
<tr>
<td>56</td>
<td>11.1 Evaluation of comfort</td>
</tr>
<tr>
<td>57</td>
<td>11.2 Evaluation of external noise and vibrations</td>
</tr>
<tr>
<td>57</td>
<td>11.3 Systematized evaluation methods based on the accumulated experience of researchers, decisionmakers and technical personnel</td>
</tr>
<tr>
<td>59</td>
<td>12 CONCLUSIONS AND RECOMMENDATIONS</td>
</tr>
<tr>
<td>62</td>
<td>LITERATURE</td>
</tr>
</tbody>
</table>
MAINTENANCE OF PAVED ROADS
Current state of knowledge and need for research

by Peter W Arnberg, Gunnar Carlsson, Lennart Djärf, Per-Gunnar Land, Georg Magnusson, Rein Schandersson, Bo Simonsson and Leif Wiman
Swedish Road and Traffic Research Institute (VTI)
S-581 01 LINKÖPING Sweden

ABSTRACT

In Sweden, about one billion SEK is spent annually on the maintenance of road and street pavements. To be able to use these resources in the best way, extensive knowledge of the consequences of various maintenance strategies is required.

The bulletin surveys the need for research in this field. The most urgent research tasks are considered to be the following:

1. Methods/models for predicting long-term changes in road/road surface condition when implementing various surfacing strategies.

2. Efficient methods for determining the structural condition (bearing capacity) of roads.

3. Measurement of current traffic loadings and prognosis of future traffic loadings (especially heavy axle loads).

4. The influence of surface condition on vehicle wear.

5. The influence of surface condition on road accidents.

6. Evaluation of effects.

However, present know-how is sufficient to begin development of planning systems for socio-economic optimization of pavement maintenance. It is therefore important that the planning systems have a flexible structure so that the newer and more reliable techniques expected from future research can be successively introduced. The planning systems must therefore be developed in close consultation between road authorities and researchers.

VTI MEDDELANDE 406 A
Since the situation regarding the municipal road network differs somewhat from the national road network (in, for example, traffic composition, road structure etc) it is proposed that two groups be formed to develop the planning systems (one for the Swedish National Road Administration and one for the municipal authorities (urban roads). It is important that these groups receive resources for system development and research so that they do not function simply as consultative groups.
1. AIMS OF THE WORKING GROUP

The aim of the working group has been to produce guidelines for coordinat-
ing research of the Swedish Road and Traffic Research Institute (VTI) into
the effects of pavement maintenance.

The best way to achieve a natural process of coordination is to focus a
considerable part of research on a critical area of application. The most
important problem in the area of pavements is at present the development
of methods for finding a socio-economically optimal strategy for the
maintenance of paved roads. There are several reasons for assigning this
question high priority.

- The cost of pavement maintenance is almost 1 billion SEK per year.

- Some people are of the opinion that maintenance is unsatisfactory and
  may lead to waste of investments made in roads and streets.

- To meet reduced grants, a changeover has been made to maintenance
  methods which are inexpensive in the short term but have unknown
  consequences in the long term.

- The "new" maintenance methods may cause road user costs for vehicle
  wear, fuel consumption etc to increase considerably more than the
  savings made by the road administrator through less expensive mainte-
nance.

- Technical progress in measuring allows the acquisition of data for large
  road and street networks at reasonable cost. In addition to road and
  traffic information systems (road data bases) information systems for
  rational maintenance methods can be built up. Large parts of such
  information systems already exist.
A research program with the aim of acquiring knowledge for optimizing pavement maintenance must be developed jointly between road administrators and researchers. The proposals presented here are therefore to be regarded as an invitation to collaboration of this type. We believe it important to describe researchers' views on the knowledge required and hope that this will lead to the initiation of a joint project aimed at developing systems for optimizing pavement maintenance.
2. GENERAL BACKGROUND

The total length of national roads in Sweden is about 100 000 km. At the end of the 1950's only 10% of the national road network was paved. Almost 100% of the paved roads have flexible pavements with a bituminous surfacing. In 1980 about 60% of the national roads were paved, and these accounted for 92% of total traffic mileage. The trend is shown in Figure 1.

As shown in the figure, increase was fairly rapid during the 60's, especially with regard to oiled gravel roads. During the 70's the increase levelled off somewhat, before resuming at the end of the 70's with the introduction of Y1G (surface dressing on gravel).

In the municipalities most roads and streets are paved. In addition, the municipalities have pedestrian and cycle paths which are often provided with a bituminous surfacing.
The expansion of the paved road and street network has thus taken place during the last 20 years and the demand for maintenance has increased accordingly.

The annual cost of pavement maintenance on national roads is at present about 500-700 million SEK and on municipality roads and streets about 300-500 million SEK.

Owing to the high increases in oil prices during the 70's the price of bitumen has risen dramatically, leading to efforts at maintenance using thinner layers or surface dressing. Instead of renewing the wearing course with 60-100 kg/m² (25-45 mm) heat treatment with 40-60 kg/m² (15-25 mm) or mechanical reshaping is used to a steadily increasing extent.

Furthermore, the interval between wearing course renewals has been extended. As a result, corrective maintenance (repair of pot holes, cracks and local minor irregularities) has increased.

What has been stated above applies in general both to national roads and to municipalities. However, the use of surface dressings has not become widespread in the latter. In larger municipalities, mastic asphalt is used to a certain extent for rut filling, a practice which is infrequent on national roads.

To sum up, a paved road and street network has been developed within a relatively short period of time and now costs about 1 billion SEK every year in maintenance. Since the paved surfaces are still fairly new, we have very limited experience of the long-term consequences of different maintenance methods.
AIMS IN MAINTENANCE OF PAVED ROADS

The general aim of road maintenance has been formulated on the basis of the 1979 decision on road traffic policy set out in the Swedish National Road Administration's (VV's) five-year plan and is as follows:

"Both individuals and industry throughout the country are to be offered satisfactory road transport standards at the lowest possible socio-economic costs."

Naturally it is difficult to define a satisfactory road transport standard for each part of the country. Such a definition can be regarded as a continuous process where increased knowledge of the effects of road maintenance is an essential part of the information required for weighing the need for maintenance resources against needs in other areas of the community. Regardless of the meaning of the concept "satisfactory transport standard", it is important that the socio-economic consequences of various maintenance strategies be considered, i.e. the latter part of the objective quoted above ("... at the lowest possible cost which is optimal for the society"). The significance of this can be understood if it is remembered that the cost of road maintenance constitutes a mere fraction of the resources consumed by traffic in the form of vehicle costs (fuel, vehicle wear, etc), time consumption and accident costs. It is therefore necessary that road administrators apply socio-economic principles in the distribution of the funds available to them.

Figure 2 illustrates the relationship between the various costs for a typical rural road in Sweden. The cost of pavement maintenance is about 25% of the total cost of road maintenance.

The figure shows that road uses costs are considerably greater than the cost of pavement maintenance. It is therefore of utmost importance to consider possible influence on road user costs when making decisions on how pavements are to be maintained. This is also valid when available resources don't permit a minimizing of the total cost. In this case, maintenance must be performed in such a way that the budgetary restrictions burden road users with the smallest possible cost increase in relation to the optimal level.
Apart from influencing the abovementioned road user costs (accident, journey time and vehicle costs) a low pavement standard and certain types of surfacing can cause road users discomfort (costs) through increased vibration and shaking, in addition to increased noise in the vehicle. This type of inconvenience (costs) may also affect those living or otherwise remaining for any period of time in the vicinity of the road. It is desirable that this type of consequence be considered in planning optimal pavement maintenance even if evaluation problems are difficult in many cases.
What objective(s) are then to govern modern pavement maintenance?

In the case of national roads these are described in the VV's "Five-year Operation Plan 1982-85".

In the Five-year Plan, the Swedish National Road Administration states clearly its ambition to be able to calculate the consequences to the community of its pavement maintenance. It is considered that available grants will not allow the same pavement standard to be maintained as in the beginning of the 70's. The cutbacks will mainly affect roads with a traffic volume of <1500 vehicles/day (approximately 70% of the paved road network) and will probably incur a loss to the community, in addition to the risk for further deterioration in road conditions.

It should be clear that if the Swedish National Road Administration is to regard a socio-economic optimization of pavement maintenance as an important objective, knowledge of the long-term consequences of various surfacing strategies, both for road users and road administrators, must be radically improved.

To obtain an idea of the objectives governing pavement maintenance in the municipalities it is necessary to turn to individual authorities since there is no significant collaboration between these. Collaboration between a number of municipalities responsible for their own roads has been in progress since 1973 within an Operating Cost Study (DKU). (At present, Gothenburg, Luleå, Solna, Stockholm, Sundsvall and Västerås are included in the DKU). The DKU published its main report in 1981. The report stated that interest concerning pavements has primarily been focussed on using comparisons of annual costs for various types of pavement maintenance in the municipalities to propose new maintenance methods for saving costs. So far, no attempt has been made to describe a standard or its consequences for road users and road keeper costs. However, it is intended that these aspects be studied in the future, since this is important in creating a basis for socio-economically optimal usage of available resources and in emphasising the arguments for increasing these.
To sum up, we consider that there are exceptionally strong grounds for a socio-economic objective being made the governing factor in planning road maintenance. Today's maintenance strategies do not appear to be sufficiently well formulated with regard to their socio-economic consequences. This arises principally through a lack of knowledge of long-term development in pavement standard (incl road surface standard) with various types of maintenance strategy and also of the relationship between road surface standard and road user costs.
A basic principle in designing the research and development program has been a close connection between research and the measures implemented. It is therefore natural to try to structure the research needed with regard to the road administrators system or guidelines for pavement maintenance.

Systems for maintaining paved roads may have various levels of complexity, depending on the extent of maintenance and its aims. Very roughly, two philosophies can be considered from which maintenance systems can be created. On one hand the road administrators may aim, with or without economic restrictions, at minimizing socio-economic costs for road transportation on the other the aim can be to formulate guidelines for an acceptable road standard to be achieved at the lowest cost for the road administrator. The two approaches converge if in the latter case the minimum requirement on the road/road surface is expressed with consideration to the effects on road users and environment.

In developing systems for pavement maintenance it is necessary to remember that the bituminous surface has two essential functions:

- It must constitute a "floor" for the vehicles using the road. The "floor" must have properties such as satisfactory smoothness, high friction etc.

- It must act as a "roof" for the road structure. The "roof" must prevent water penetrating the roadbase and sub-base and also contribute to delaying disintegration by distributing the wheel pressure over a larger area.

Design and application of various systems for maintenance of paved roads are being studied at several places in the world. However, a considerable difficulty at present is that the relationships between road user effects (accidents, journey times, vehicle costs) and road standard are insufficiently known. This leads to the risk of the system attaching too little significance to these effects in relation to the road administrator's costs. The risk of socio-economic "waste" is evident if it is remembered that road user costs are considerably higher than the maintenance costs for paved
roads (cf Section 3 above). The risk also appears to increase in times of economic restriction when road administrators seek to reduce their costs.

To avoid socio-economic sub-optimization, systems for pavement maintenance need to be developed which take into account the effects on the road user and others in relation to socio-economic significance.

Such systems make it easier to see which elements are included in pavement maintenance and the relationships between them. This provides better possibilities for clarifying:

- which variables can be obtained by processing information in various data bases, such as road data bases, pavement data, traffic data and weather data from the SMHI (Swedish Meteorological and Hydrological Institute).

- which variables are to be measured and stored and where and how they are to be measured.

It may be appropriate here to remember that pavement wear is also influenced by other roadkeeping measures such as snowclearing, draining and winter maintenance. For example, the more the salting in wintertime, the less severe the ice and snow conditions. This means that vehicles with studded tyres cause wear on the road surface instead of the snow layer.

A system for pavement maintenance must therefore be designed so that it can be integrated with other systems, such as those for winter maintenance.

Figure 3 shows a possible design for a system of this type. The diagram also gives examples of external information sources (data bases) which may be usable.
However, it is not self-evident that there is only one maintenance system which can satisfy every road administrator's needs. The Swedish National Road Administration probably requires a system for maintaining paved roads which is different to that suitable for a municipality. Even municipalities of different sizes may require different maintenance systems.

A maintenance system may include different strategies for maintenance of paved roads of various types, such as various traffic classes or geographical areas. It is important to remember that the concept of "strategy" relates to several maintenance cycles (ideally the whole lifetime of the road) and that the type of maintenance, like the time interval between maintenance activities, may differ. Section 5 below gives a more precise definition of the strategy concept.

In order to design a maintenance strategy which takes socio-economic consequences into account, knowledge of the following areas is required:
- Road administrator costs for maintenance of a paved road.
- The road's expected performance.
- Road user and environmental costs as a function of road condition.

Since it is often impossible to study directly the relationship between various surfacing strategies and road user costs, the performance of the road must be studied. The performance variables considered significant for road users and for the further deterioration of the road are normally termed "functional properties" of the road surface and of the road.

The following properties are significant for the road's function:

- Roughness
- Ruts
- Overhanging pavement edges
- Cracks
- Alligator cracking
- Pot holes
- Crossfall
- Macrotexture
- Microtexture
- Friction
- Light reflectance

In order to determine the costs for the road administrator, road users and others, models/interrelationships must exist, describing how the costs vary with road/road surface properties or condition. Knowledge of how the functional properties change with time under the influence of traffic and climate is also necessary.

A maintenance strategy can lead to both direct and indirect costs for the road administrator. The direct costs consist of costs for renewing the wearing course, for corrective maintenance (repair of cracks, pot holes etc) during the period between two renewals. The indirect costs are those arising through underdimensioned maintenance which may in the long term
lead to structural deterioration of the road. Section 5 below provides a general description of current knowledge and research needed, both for designing maintenance strategies and for developing models of the change in functional condition of the road/road surface under the influence of traffic and climate, etc. The structural condition of the road and methods of measuring this are described in Section 8.

Sections 6 and 7 discuss current knowledge and research needed regarding the relationships between road surface condition and effects on the road user (Section 6) and the environment (Section 7). This area of research sets demands on objective definition and measurement of road surface condition (Section 9) and evaluation of the effects (Section 11).

Knowledge of present and future traffic loads forms the basis for quantifying road user effects and using models for the change in road/road surface condition. Section 10 describes traffic measurements and traffic prognoses.
5. PAVEMENT PERFORMANCE

Deterioration of the road surface with time is mainly the result of traffic and climate contributing to the following processes which destroy the road structure:

- surface wear
- deformation in the bituminous pavement
- structural deterioration
- frost and ground processes in the sub-grade

These deterioration processes result in changes of the properties of the road surface, e.g. texture, rutting and roughness.

As a result of these destructive processes, the road must be maintained by the road administrator who can choose between two different approaches. Frequently the wearing course is renewed at certain intervals of time by resurfacing with new material. A new wearing course may consist of a surface dressing on a road surface levelled with asphaltic concrete or it may consist wholly of asphalt concrete. After such maintenance has been repeated a number of times, strengthening in order to improve the structural condition of the road may be economically motivated. Between maintenance occasions repairs may be carried out in the form of infill of eventually occurring pot holes and crack sealing. The strategy described is designated I in Figure 4.
Instead of strengthening as in strategy I, reinforcement may be included in the wearing course renewal so that it is made "thicker". For example, the thickness may be increased from 60 kg/m² to 80 or 100 kg/m². Such a strategy is shown in the diagram as alternative II.

The maintenance measures and intervals provided in this strategy are adapted by the road administrator with regard both to the condition applying at time A:

- road surface condition
- road structure condition (pavement condition)

and also to the expected performance which depends on:

- traffic
- climate
- winter maintenance (e.g. salting, snow clearing)

among other factors.
At present, we have insufficient knowledge of the relationships between on the one hand, changes in road/road surface condition and on the other hand, maintenance action, traffic and climate. Extensive research appears necessary. Some of the most important research problems are described below.

The research problems are presented under headings corresponding to the deterioration processes described on the previous pages. In order for acquired knowledge to be used in systems for optimizing pavement maintenance the systems must be summarized in a model describing how road/road surface condition changes with time in connection with various actions or maintenance strategies.

In some cases, "secondary" research problems are described, these referring to problems not directly related with maintenance optimization.

5.1 Surface wear

Vehicle traffic (especially vehicles with studded tyres), snow clearing vehicles and also climatic conditions contribute in time to surface wear. Studded tyres are the cause of the larger part of such wear.

5.1.1 Wear from studded tyres

To be able to determine the amount of wear from studded tyres, information is needed on the abrasion resistance of the wearing course and the expected number of passages by vehicles with studded tyres. Here it is not only the total abrasion that is of interest but also the abrasion occurring in ruts caused by vehicles following each other's tracks. Abrasion also affects microtexture and macrotexture of the wearing course.

The abrasion resistance of plant-mixed pavements is normally expressed in the form of an SPS* index (mass of abraded material in tons per km road and million vehicles with studded tyres). At present, the SPS index of

* SPS = specific wear.
various plant mixes is known in approximate terms. It has not been possible to develop a corresponding index for surface dressing mainly because of the special measuring problems associated with a coarse macrotexture. It is important that a measuring method be developed in this area since the use of surface dressings is very widespread (see Chapter 9.2).

A large number of factors influence the magnitude of the SPS index; aggregate, binder, degree of compaction (in plant mixes), tyre stud design, stud projection, number of studs per tyre, etc. Special attention must be paid to studs in truck tyres where these are used. At present, little is known about the influence of these factors. Consequently, the following research is proposed for determining the abrasion resistance of wearing courses.

Hitherto, the abrasion resistance has been determined through measurements of test surfaces in the field, which has meant that evaluation takes a great deal of time. An accelerated test procedure, for example, with a test road machine of the type proposed in VTI Meddelande 223, 1980, and which has been discussed in the project group for Inter-Nordic research into studded tyres, is desirable. This would make it possible to study the influence of the factors mentioned above. The abrasion indexes obtained in accelerated testing would, together with information on climate, number of vehicles with studded tyres etc, be used to predict the development of surface wear. It is important that tests with surface dressings and open-graded or porous wearing courses can be conducted.

It should be possible to complete an installation of the above mentioned type 1-2 years after coming to a decision.

Abrasion influences both the microtexture and the macrotexture of the wearing course. Concerning the significance of the texture for "road surface condition" and vehicle costs, a more detailed study of the changes in texture in various wearing courses would be of interest.
5.1.2 Other surface wear

The stresses from tyres travelling on a road surface may result in stones in the wearing course being torn loose or crushed. The high SPS indexes usually obtained on roads with a relatively low frequency of studded tyre use indicate that plain tyres cause a not insignificant proportion of the wear in wintertime. The degree of wear at other times of the year is largely unknown.

Abnormally high wear which cannot fully be attributed to studded tyres has occurred in plant mixed pavements in recent years. The cause appears to be shortcomings in application (for example, separations) and insufficient adhesion between the bitumen and the mineral aggregate.

Extensive research aimed at clarifying the influence of various factors (construction material, design) on abrasion resistance in the wearing course appears necessary.

5.2 Deformation in the bituminous pavement

Material depression in the pavement may change the texture of the wearing course and/or lead to rutting, the principal cause being heavy traffic. Changes in the texture of the wearing course result from stones in the road surface being depressed further into the road structure by traffic. As an example, stones in a surface dressing may be inbedded in the road pavement, thereby reducing the available voids for the binder. If the voids become insufficient in relation to the binder volume, bleeding may occur. Both the macrotexture and the microtexture are altered.

Rutting as described above is a consequence of deformation through instability of the wearing course (the uppermost pavement course) or at a lower level within the bituminous pavement.
5.2.1 Texture changes

Texture measurements have so far been made only to a limited extent, which means that little is known of changes with time in the texture of various wearing courses.

If a newly developed method of measuring and collecting relevant data on texture can be used (see 9.5) it will be possible to acquire better knowledge of texture changes.

In the case of surface dressings, a secondary research requirement for this program would be a method for determining the binder need in order to avoid both bleeding and stone loosening.

5.2.2 Rutting through plastic deformation

Rutting may occur due to plastic deformation in the uppermost pavement layer if this has an unsuitable composition, or in the wearing course or levelling course which occupies a lower level in the pavement after one or more resurfacings. In the latter case, the wearing or levelling course will be subjected to stresses for which it may not have been formulated. At the VTI research into this problem has been in progress since 1977 and is aimed at producing better criteria for proportioning. The need for further research lies in:

Assessing the risk of plastic deformation after resurfacing. The method developed at the VTI for loading beams taken from an existing pavement is too complex for routine use. A method for predicting risks of plastic deformation after resurfacing on the basis of the properties of smaller pavement samples (e.g. drilling cores) should be developed.

Methods of clarifying the causes of rutting. There is a need to develop diagnostic methods, (is rutting due to surface wear, plastic deformation in the pavement or insufficient bearing capacity in the roadbase?). The cross-profile and profile analysis may therefore be considered to be a diagnostic aid. If roughness in the longitudinal and lateral direction
directions is followed up continuously it may be possible to determine the causes of rutting from roughness variations at different seasons (see Section 9).

Secondary research needs are the following:

Mix design criteria for wearing courses. The present criteria mainly take into account the requirements on wearing course material when used in the wearing course. Which criteria are then to apply if the future performance of the material at a lower level in the pavement is also to be taken into account? Field tests combined with laboratory experiments (beam tests, creep tests, etc) together with studies of the mechanisms should bring us nearer this goal.

Rut-repair methods. Among the repair methods which should be tested further are milling and resurfacing or resurfacing alone.

5.3 Structural deterioration

The stresses arising in the road structure when loaded give rise both to permanent and elastic deformations. Permanent deformations at different levels accumulate to cause rutting in the road surface, while elastic deformations within a larger or shorter time - depending on the elasticity of the underlaying layers - cause cracks or alligator cracking of the pavement. The term "structural deterioration" refers to the processes described here.

5.3.1 Rutting through permanent (plastic) deformation in unbound courses including the subgrade

Section 5.2.2 above describes rutting in pavements caused by plastic deformations, i.e. deformations which are primarily the result of instable (unsuitably composed) pavement materials. In this type of plastic deformation there are no or only negligible volume changes. Another type of permanent deformation may be caused by the traffic load, which succes-
permanent deformation - is of special interest in thin pavements, while stresses on the formation level and in the unbound pavement material are greater than with thicker pavements (in the latter case it appears that rutting in the underlying, unbound material is negligible).

In the AASHO tests approximately 68% of rutting was shown to be due to unbound pavement and subgrade materials. In general, it is important to clarify the causes of rutting (instable pavement material and/or instable unbound material and/or successive compaction primarily of unbound material, including the subgrade) with a view to the relationship between cause and action.

5.3.2 Cracks and alligator cracking

Cracks in pavements are either the result of traffic loads or movements in the road structure (settling, frost processes). Longitudinal cracks due to traffic loads originate in the surface at the edges of the ruts or in the lower edge of the pavement at the bottom of the rut. Longitudinal load cracks - which appear less common than lateral cracks - originate in the ruts both in the upper and probably also the lower edges. Traffic load cracks generally progress to alligator cracking unless action is taken. However, alligator cracking can occur without being preceded by an initial "cracking" phase. The cause lies in weaknesses in the road structure - either in the (unbound) roadbase and/or in the sub-base and/or the subgrade. Previously, this type of damage has been attributed to underdesigned pavements (or increased traffic loads). The problem has again become relevant in recent years through the use of low quality materials in the upper courses of the pavement. Examples include shale which in a crushed form has an unacceptably high fine material content. In combination with water accumulation this can lead to surface softening. In bearing capacity measurements there are certain possibilities for assessing at which levels in the road structure weak layers occur by measuring deflections at several points. These possibilities should be studied in more detail.
In concluding this section, attention should be drawn to cracks of thermal (low temperature) origin which occur in the colder regions of the country. The influence of these on the future development of pavements should be given greater attention than hitherto.

5.4 Frost and ground processes

Height irregularities, cracking and rutting may occur through frost processes. Irregularities and cracks occur in frost heave while thawing leads to rut formation. The damaging effects of ground heave depends on roads design, subgrade conditions and climate and weather.

The effect of a particular technique in pavement maintenance depends partly on frost activity in and above the road. Frost heave irregularities in the road surface ought to be less severe in Skåne (southern Sweden) with its mild winter climate corresponding to a mean cold quantity of 2 400°C x h* compared with northernmost Sweden with a harsh winter climate corresponding to a mean cold quantity over 28 800 °C x h. If the size of the average frost heave is compared, a figure of 2 cm for Skåne and over 24 cm for northernmost Sweden is obtained, other road conditions being similar. In the same way, comparisons can be made for other types of frost influence on roads. For example, the risk of longitudinal frost cracks is more tangible only when the mean cold quantity exceeds 14 400°C x h.

A prerequisite for frost causing damage to the road during the frost heave period is that the subgrade is frost-susceptible, i.e. it responds to frost penetration with frost heave. The frost susceptibility of the sub-grade depends in turn on the soil types it contains, soil layer conditions and ground water conditions. The development of damage in the road is determined by the structure of the pavement.

* Mean cold quantity, expressed in negative °C x h, is calculated as the sum of all negative monthly mean temperatures during the winter in question, multiplied by 30 x 24.
In assessing the effects of a certain technique for pavement maintenance with regard to frost activity it is necessary to know the extent to which this is controlled by the following types of conditions:

- climate and weather
- pavement
- subgrade
- run-off

The damaging effects of frost in a road pavement including the surfacing are fairly well known as a function of climate and weather, principally qualitatively but to a certain extent also quantitively. However, experience is dispersed and has not been summarized, so research should be designed with the aim of studying the regional (climate-dependent) distribution of various types of pavement damage (frost damage). The value of the project lies in determining the regions for which the different techniques for pavement maintenance are most suitable.

If the pavement is built on non frost-susceptible material, the frost processes in the subgrade will primarily be decisive for the influence of frost on the road. Assessing the development of frost damage on the basis of possible indications from the subgrade is an old problem related to the complexity of the subgrade. With regard to physical frost processes, in particular those relating to frost penetration, a method for calculating the degree of frost heave has been developed at the VTI. The calculation method includes an expression for frost heave susceptibility which is determined by equipment designed by the VTI. Research into the method is in progress.

Research into those physical processes relating to thawing is also continuing. Studies concern the complex interrelationships in thawing when surplus water accumulates in the soil layers at the same time as it drains off, and the effects these processes have on the road's bearing capacity and deterioration from traffic. Although dispersed and uncoordinated, considerable knowledge has been built up over the years concerning subgrade conditions and their significance for frost activity, in addition to the effects of the latter on the road structure. The different types of subgrade
in Sweden have a regional distribution according to types of geological deposits. The geology of each area thus decides the structure of the materials in the subgrade. The other significant factor in the frost process, i.e. ground water conditions, is determined by the hydrogeology, i.e. the type of terrain and the geological structure of the subgrade, in addition to climate and weather.

A project to study the dependence of pavement damage (frost damage) on subgrade type is proposed with the primary aim of coordinating the experience gained so far. The value of the project lies in obtaining information on which subgrade types are most suited to the various techniques for pavement maintenance.

5.5 Performance models

In order to predict how the condition of a road will change due to structural deterioration, a model or method is required which describes the rate at which a road designed with a certain structural strength of the subgrade deteriorates under the influence of traffic and climate. Such a model may be empirical or analytical or a combination of these.

An empirical performance model requires systematic observations over a long period of time of the deterioration sequences in various road designs. Owing to the time and cost involved in collecting the large quantities of data required an empirical model is not regarded a realistic first choice, especially since corresponding systematic observations must also be made for various strengthening measures. This situation may, however, change with the development of quick and relatively inexpensive methods of accurately measuring road condition (see Section 9). Unfortunately, the measuring capacity regarding the structural condition of a road is still insufficient to allow a comprehensive inventory. With the development of laser technology, however, there is cause for certain optimism in this area (see Section 8).
With an analytical performance model it is in principle possible to estimate changes in road condition both before and after various strengthening measures.

An analytical model is built up around a suitable theory. The classical theory of elasticity is generally accepted in this context and is used for calculating stresses and strains in the road structure resulting from traffic loads. Here it is of great importance to use representative values for the mechanical properties (E-modulus and Poisson's ratio). The mechanical properties vary for different parts of the road structure owing to seasonally dependent variations in condition (pavement temperature as well as temperature and moisture in unbound layers and subgrade). There is a great need for studies of these variations, especially with regard to properties during thawing, in order to be able to estimate bearing capacity variations throughout the year on the basis of measurements at a particular time.

Apart from this, changes in road performance are of a stochastic nature (depending on natural variations in material properties, layer thicknesses, binder contents, voids, etc). A performance model must therefore be based on a sufficient quantity of data to allow a statistically based description to be made, i.e. in applying the model the expected performance is expressed in statistical terms (probabilities).

Research needs for obtaining an applicable analytical/statistical performance model also include studies to determine which forces (stresses and strains) can be permitted for various material layers in the road structure, for various Swedish subgrades and for various external factors. The permitted values or criteria in use today have been produced in other countries and under assumptions which do not fully agree with Swedish conditions, especially with regard to subgrade material and climate. In order to test the validity of existing criteria and adaptation to Swedish conditions, field and laboratory tests on the deformation and strength properties of various materials are necessary.

A facility for making accelerated full-scale tests (e.g. with a larger road test machine) would be a great asset in complementing other studies.
With an analytically based performance model as above it is possible to calculate the probable lifetime of various road structures or the total traffic load that can be permitted before deterioration has progressed so far that the pavement shows alligator cracking and/or that permanent deformations in unbound material and subgrade result in unacceptable rutting of the road surface.

In order to describe pavement performance, a model is required which can describe the relationship between deterioration and the parameters influencing this, i.e. traffic and climate. Such models have been developed in other countries, principally the USA. They are often semi-empirical and are based on results from the AASHO test. Although these models describe the deterioration sequence they do so almost exclusively on the basis of changes in road roughness.

In this context changes in roughness are primarily an expression for road user comfort. This is unsatisfactory for describing pavement condition from the road administrator's viewpoint. To produce an adequate description for this purpose, rutting and occurrence of cracks and alligator cracking should also be included. Pavement condition is then described in the form of a "pavement index" which is obtained by weighting the three condition parameters mentioned above.

To produce a Swedish model, it is possible to use a model altered in this way and adapt it to Swedish conditions. However, this demands a large quantity of data. The research needed for such a model thus includes a systematic follow-up of the change in condition of a number of roads with different structures, bearing capacity and traffic in various parts of the country. The change in condition can be determined through repeated measurements of road surface roughness and rutting, damage surveys, bearing capacity measurements using analyses of falling weight measurements (multiple point measurements) and information on actual traffic loads via axle load measurements or via a model for estimating actual traffic load (see Section 10.1).

Apart from the road/road surface changes resulting from structural deterioration, the complete performance model also comprises surface wear, plastic deformations in the pavement and frost processes.
The development of such a model is absolutely necessary in order to make a socio-economic optimization of maintenance of paved roads, and it is therefore proposed that this area be given high priority. A project with the aim of developing a suitable model was started in 1983 by the VTI at the request of the Swedish National Road Administration.
6. EFFECTS ON TRAFFIC OF PAVEMENT SURFACE CONDITION

As mentioned above, road user costs consist of accident costs, time-related costs and vehicle costs. To road user costs are normally added inconvenience or nuisance caused to road users through noise, vibration, etc. The latter are often included in the term "comfort".

The research problem lies in describing and quantifying how these costs vary with pavement surface properties or condition. A solution to this problem requires knowledge of how pavement surface properties affect traffic variables, i.e. accidents, journey time, fuel consumption, tyre wear, vehicle wear, damage to goods, and comfort/performance.

The following table indicates the pavement surface properties considered to be significant for one or more of these variables. The table makes a rough assessment of whether influence of the individual property of the pavement surface is low (1), moderate (2) or high (3). In those cases where no direct influence is considered to exist, the area has been shaded.

<table>
<thead>
<tr>
<th>Property of pavement surface</th>
<th>Traffic variable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accidents</td>
</tr>
<tr>
<td>Crossfall</td>
<td>2</td>
</tr>
<tr>
<td>Ruts</td>
<td>3</td>
</tr>
<tr>
<td>Roughness</td>
<td>2</td>
</tr>
<tr>
<td>Friction</td>
<td>3</td>
</tr>
<tr>
<td>Macrotexure</td>
<td>3</td>
</tr>
<tr>
<td>Microtexture</td>
<td>3</td>
</tr>
<tr>
<td>Light reflection</td>
<td>3</td>
</tr>
</tbody>
</table>

VTI MEDDELANDE 406 A
Note that the table only indicates the relative significance of the various pavement surface properties for each traffic variable individually. The traffic variables (columns) cannot be compared against each other.

The following part of Chapter 6 provides a general survey of current knowledge and the research needed into the influence of the various properties on traffic variables. The section dealing with influence on journey times also takes up the problems that maximum permitted axle loads or road closures cause for road users.

6.1 Traffic safety - accidents and indirect measures of traffic safety

The relationship between traffic accidents and road surface condition (friction, rutting, roughness, etc) is very little known. In Sweden, the VTI has used data from the 1977 pavement inventory of the national road network to study both how the type and condition of the pavement influence the accident rate. The first results (VTI Meddelande 242) showed weak, statistically nonsignificant tendencies towards a lower accident rate (number of accidents per million vehicle km) for surface dressed roads compared to roads with asphalt concrete. In the study, neither the pavement condition, which was judged subjectively in the inventory, nor indirect measures of condition (pavement age and number of axle pair passages since pavement maintenance) could be shown to have any significant relationship to the accident rate. The analyses did not take account of road alignment.

Since surface dressed roads in 1977 probably had a poorer alignment than reshaped or asphalt concreted roads, a positive effect of surface dressing may possibly be concealed. On the basis of friction measurements, one might expect such an effect when the road surface is covered by thin ice or snow or when it is wet. The analysis was therefore extended to take into account "good" and "bad" weather (it was not possible to make a direct division into different road conditions), classified by precipitation quantity and mean temperature. It was found that asphalt concrete roads have a notably higher accident rate in "poor" weather than in "good" weather, while surface dressed roads show very much weaker weather dependence (VTI Meddelande 317).
Within the Nordic countries, certain studies have been made in Finland of the relationship between pavement type/condition and traffic accidents, while studies made outside the Nordic countries have focussed on the effect of friction on the accident risk. The information gathered from these studies indicates that low friction (less than about 0.4) leads to a significant increase in accidents. Several studies show also that surface dressing of road stretches with a high number of accidents on wet surfaces leads to a large reduction in this type of accident. However there are strong reasons for questioning the results from the latter type of study owing to the sampling bias in this type of before-and-after studies.

Since accident costs constitute a significant part of road user costs, at the same time as knowledge of the relationships between road surface condition and accidents is very inadequate, it is appropriate to apply extensive resources to this area of research. A considerable problem, however, is the difficulty of distinguishing the significance of road surface condition from other factors such as alignment, road user behaviour etc.

To clarify these relationships, accident analyses must be complemented both with studies of road user behaviour (e.g. speed adaptation, lateral positioning etc.) and other types of study. The latter include studies of how drivers are influenced by functional properties such as rutting, roughness, etc.) see Section 6.4 below, and studies of how vehicle manoeuvrability is affected by these properties (e.g. use of vehicle dynamics models). Furthermore, worthwhile studies of the relationship between traffic accidents and road surface properties (pavement type, roughness, ruts texture, friction, etc.) require the latter to be measured in very large road networks and that the information be continuously updated. With the present rapid development in integrated systems for measuring road surface properties and the great interest shown by the Swedish National Road Administration in these questions, it should be possible within about a year to measure road surface properties, at least on the main road network. It is more uncertain whether resources allow measurements to be made on urban roads. Finally, it is of great value for accident studies, if the geometrical standard of a road, the road alignment, has been measured and can be taken into account in an analysis, in addition to easily accessible data on traffic volumes and variations being available more or less as at present.
6.2 **Journey times/transport facilities**

Studies made so far in Sweden indicate that pavement surface condition has a relatively small influence on car drivers' speed and thus on their journey time. Measurements have been made on relatively rough and rutted roads before these received a new surface dressing. The measurements were repeated after dressing and it was found that car speeds had increased by 1-2 km/h, which corresponds to a reduction in journey time of about 2%.

With the relationships between journey time cost and cost of pavement maintenance exemplified in Figure 2, Section 3, 1% of the journey time cost corresponds to about 15-20% of the cost for pavement maintenance. Thus, if it were possible through an alternative strategy to achieve a 1% reduction in journey time cost, this would in socio-economic terms motivate an increase in cost for pavement maintenance of up to 15-20%, all other factors being unchanged. Increased speed would however lead to an increase also in vehicle cost which in the 80-100 km/h range is of the same order of size as the reduction in journey time cost. Therefore the need for more extensive studies of the relationship between road surface condition and journey times should be based on calculations of the net gain in journey time cost and vehicle cost. We do not believe that an analysis of this type (which ought to be made) would necessitate so much further research into the relationship between pavement condition and journey times by car on rural roads.

The above applies to passenger cars only. Knowledge of the influence on the journey times of heavy vehicles is inadequate. There is a great need for empirical studies of the relationship between pavement condition and journey times for heavy vehicles on roads.

In urban areas the influence of pavement condition on speeds/journey times is assumed to be small compared with other factors. However, no empirical studies supporting this assumption have been found.

Journey time losses occur also when maintenance activities are in progress. In general, these losses are likely to negligible and no specialized research
for quantifying them is necessary. However, they should be included in a model for optimizing pavement maintenance so that they are not ignored in those cases where they may be significant.

Different surfacing strategies lead to different degrees of restriction on heavy traffic. The consequences of temporary reductions in maximum permitted axle load must be included in the optimization model. Relatively extensive research is needed in this area since present knowledge is very poor.

6.3 Vehicle costs

Pavement surface condition may exert a great influence on vehicle costs. Since this cost constitutes a large part (often the largest part) of the total road user cost it is exceptionally important that extensive research resources be applied to studying the relationship between, on the one hand, pavement types and pavement surface condition and on the other hand, various components of vehicle cost.

Those vehicle costs which depend on pavement type and pavement surface condition are:

1. Fuel consumption
2. Tyre wear
3. Vehicle wear

Added to these are possible damage to goods and costs for extra packaging of goods to the extent demanded by the condition of the road surface.

The distribution of the vehicle cost between the above components varies between vehicle types and road and traffic environments. Especially large differences in the latter case are found between urban and rural areas.

The dominating costs are vehicle wear and fuel consumption, while tyre wear accounts for a smaller part. However, research results indicate that tyre wear may vary considerably with road surface properties, so these aspects are also interesting to study in this context.
Studies of relationships between road surface properties and vehicle and tyre wear demand extensive resources. Before any larger Swedish studies are planned, the comprehensive studies made in Brazil and India should be analysed thoroughly with regard to their applicability to Swedish conditions.

6.3.1 Fuel consumption

Several studies have been made of how various pavement types and road surface conditions influence the fuel consumption of cars. Almost all Swedish studies have been made on rural roads. At present we know that:

- Surface dressing instead of asphalt concrete leads to an increase of about 5% in petrol consumption of cars on a straight, level road when the surface dressing is new and 1-3% when the surface dressing is a few years old.

- Rutting does not appear to influence the fuel consumption of cars. These measurements were also made on a straight, level road.

Studies of the relationship between the fuel consumption of a vehicle and the coarseness (macrotecture) of the road surface have been started at the VTI. Preliminary answers to the following two questions have been obtained:

1. To what extent is vehicle fuel consumption influenced by the coarseness of the road surface?

2. Which parts of the texture (wave lengths) has the greatest influence on fuel consumption (rolling resistance)? This question has already been satisfactorily answered in the case of noise.

The answers to these questions are of great importance when optimizing road surface texture to give low fuel consumption without detracting from friction.
Further studies of how various road surface conditions influence fuel consumption are desirable.

In order to be used in an optimization model, it is necessary for fuel consumption to be expressed as a function of the condition variables recorded for the road surface and which constitute the information used by the road administrator in deciding the maintenance need. The Swedish National Road Administration has, for example, developed vehicles for measuring rut depth, crossfall, longitudinal irregularities and in the future texture will be included. Fuel consumption as a function of these indexes needs to be studied both for cars and heavy vehicles. The vehicle cost model developed by the VTI should be applicable in generalizing the measurements to the Swedish vehicle fleet and to different road standards.

Measurement of fuel consumption is relatively simple. Models for the relationships between road surface properties and fuel costs applicable in an optimization system for rural roads should be available in about 2 years, and for urban roads and streets in about 3 years.

6.3.2 Tyre wear

Tyre life is of great importance, firstly in terms of purely private economy to the car owner but also in terms of the national economy. By adapting his driving technique, the motorist can himself determine tyre wear to a high degree, but basically tyre life is also a question of tyre and road surface properties.

The tyre industry is working continuously on producing more wear-resistant tyres. However, the industry has not paid much consideration to individual road surface parameters.

Tyre wear questions are becoming successively more prominent since many roads are being maintained through surface dressing instead of a new wearing course of asphalt concrete. Surface dressing normally has a considerably coarser texture than the plant mixed pavement it is intended to replace.
As a rule, road surface texture is regarded one of the decisive factors for tyre wear and it is considered rightly or wrongly that a coarse surface must wear out tyres more quickly than a smooth surface. However, road alignment cannot be neglected. The forces which must be absorbed in the contact area between tyre and road surface through the crossfall of the road, in driving round a curve etc., naturally cause a certain proportion of tyre wear.

Natural tyre wear, i.e. wear occurring in normal car driving, is the cumulative result of several complicated physical sequences. According to a view widely accepted at present, tyre wear is mainly caused by three processes, which, especially in the case of the first and third, require some type of relative movement between tyre and road surface:

**Abrasion.** Angular irregularities in the road surface, often very small, cut and tear away tread material from the tyre. The friction arising in conjunction with this process is often high.

**Fatigue.** Rounded irregularities in the road surface cause fatigue and fragmentation of the tread material through repeated changes in form. The friction linked with this process is low.

**Blistering.** On smooth surfaces, soft tread material affected by friction can create small blisters or rolls which are successively torn away. Friction in this process is high.

The three processes occur in combination in overall wear. Apart from the influence of the third process normally being less than the two others, the individual contributions to overall wear are difficult to identify. In addition, interactions occur; for example, the reduction in strength of the rubber as a result of fatigue contributes to an increase in abrasion. It is also worth noting that the condition for a certain relative movement between tyre tread and road surface is fulfilled even in free rolling. The tread, which in the free condition is double curved, must be flattened continuously in the contact area during rolling and this cannot take place without relative movements. The higher mileage of radial tyres compared to crossply tyres is explained in part by the reduced extent of such movements.
It is quite clear that well-planned practical tests reflect natural wear in a correct way but the tests are very expensive and time-consuming, especially if they are to be repeated on road surfaces with different textures, alignment and cross-profiles.

Two studies of this type have been made at VTI with a car in order to quantify differences in wear between surface dressing and plant mixed pavements. Both these showed that wear was 50-80 % greater on surface dressing than on plant-mixed pavement. The results of these studies have been questioned and better controlled experiments have been conducted in a test road machine. These show that tyre wear on a new surface dressing is more than double the wear on a new plant-mixed pavement. It remains unclear how worn pavements influence tyre wear.

As mentioned before, tyre wear results from the interplay of forces between tyre and road surface and a very large part of the wear appears to occur in conjunction with cornering, braking and acceleration. According to the foreign literature, the microtexture is the most significant property of the road surface. What we know today is that tyre wear varies considerably and that the influence of the road surface is probably critical, although it is unclear in which way.

Further studies are therefore desirable, especially since this proposal for a research program also includes urban areas. The choice of wearing course type in urban areas is probably of great importance for tyre wear, in view of all the retardations, accelerations and changes of direction which are characteristic of urban driving.

It is also important to study tyre wear in heavy vehicles and its dependence on road surface properties.

6.3.3 Vehicle wear

During the 60's and 70's operating costs for road vehicles in relation to road administration cost have attracted increasing interest in different places around the world. In Sweden this question has primarily been studied by the
Swedish National Road Administration and the Association for Bituminous Pavements, while internationally the World Bank appears to have been the most active body.

Repair costs, together with depreciation costs, which are to a certain extent dependent on repair costs, constitute over half of the total vehicle cost. It has also been suggested that vehicle operating costs and depreciation are of a very much higher order of magnitude than the costs of road construction and maintenance. Pavement maintenance costs have thus been stated to be less than one per cent of total road user costs. The dependence of fuel costs on road standard is relatively insignificant compared to other components of the total vehicle cost, which is interesting in view of the great interest in the relationship between fuel consumption and road environment in Sweden in recent years. However, the background to this lies in an expected shortage of fuel.

Transportation Research Record 702 gives the following relationship between road roughness expressed in PSI and relative spare parts cost. The relationship is based on a study covering more than 500 buses in Brazil.

<table>
<thead>
<tr>
<th>Road roughness PSI</th>
<th>Relative spare parts costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>59</td>
</tr>
<tr>
<td>3.5</td>
<td>100</td>
</tr>
<tr>
<td>2.5</td>
<td>180</td>
</tr>
<tr>
<td>1.5</td>
<td>260</td>
</tr>
</tbody>
</table>

As can be seen, the effect of road roughness on spare parts cost is very great.

An American study states that in nearly all vehicle components wear damage consists of accumulated fatigue damage. Fatigue damage is defined as the inevitable loss of lifetime as a result of varying stresses. For a vehicle travelling on a rough road the static forces due to the vehicle's weight will combine with dynamic forces initiated by road roughness. The
accumulated fatigue damage in a vehicle component can therefore be regarded as an economic expression for the surface standard of the road.

An urgent area of research is the study of the relationship between road roughness and stress in vehicle components. This can be investigated by selecting a number of road sections and measuring the longitudinal profile with a GM profilometer together with. For these road sections the stresses are measured in one or more vehicle component(s) assumed to be dependent on road roughness.

Measurements of road roughness with the GM profilometer have an advantage over other types of roughness measuring system in that they provide a detailed picture of the road's longitudinal profile which makes it possible to obtain information on the wavelength distribution of road roughness on the various test sections.

Using the measurements of stress variations in vehicle components as a basis, a calculation can be made for each road section of the theoretical lifetime of each component. The theoretical lifetime can then be compared with various general measures of road roughness, for example, the RMS value (Root Mean Square) of the profile amplitude of the road.

The relationships between theoretical and actual lifetime can be studied both through fatigue tests in the laboratory and also by investigating the extent of repairs to components in the vehicle whose exposure to road roughness is more or less known (as in the truck fleet of the Swedish National Road Administration).

6.3.4 Damage to goods

One area which has almost completely been neglected is the significance of the road surface regarding damage to goods. The Swedish Institute of Packaging Research states that damage to goods costs 500 million SEK per year. Even if a large proportion of these costs arises through damage in handling, damage from the road may be considerable. Damage may occur through impacts arising from road surface irregularities which smash the
goods, and also through road surface texture creating vibrations which lead to separation in the goods (such as electronic components, refrigerators, paints etc).

The first task in research in this area should be to obtain information on which impacts and vibrations the goods are exposed to in road transport. Following this, goods can be exposed under controlled conditions in the laboratory to similar impacts and vibrations in order to measure and record the damage that occurs. Using mathematical simulation of the road environment, vehicles and packaging, the effects of changes in the road environment can be studied and demonstrated in the form of calculated stresses in goods.

6.4 Comfort and performance

Effects of the road surface in the form of wear, petrol consumption etc are often assigned great importance at the expense of effects on humans. This is largely because it is difficult to evaluate in economic terms discomfort, fatigue, reduction in capability and working performance, etc. In particular, the negative effects that can result from road induced vibrations transmitted by the vehicle to the driver and which appear after the vibrations have ceased or decreased in intensity are seriously neglected. Those effects may be due to vibrations, poor road geometry, rutted roads, poor visual guidance etc often activating the driver at the same time as they cause fatigue. After-effects occur both because of the direct effect on the driver and also because of the compensatory extra effort required to counteract the direct effects. This form of fatigue can lead to accidents even on good roads or in other contexts, such as the home or workplace.

At the VTI, research has been conducted into comfort assessment on roads and fatigue and performance in simulators. Further work, especially on after-effects using the tested methods, is necessary to establish the effect of the road surface on comfort, fatigue and performance.

Activation and fatigue measurements, studies of driving behaviour and comfort assessments according to methods already developed should be
carried out. The results can be used both to predict accidents and to clarify the remaining comfort factor which, although it does not affect accidents, has a certain intrinsic value.
7. EXTERNAL EFFECTS OF PAVEMENT SURFACE CONDITION

Environmental disturbances in the form of noise and vibrations has attracted increasing attention in recent years. Noise increases human stress and experiments have shown that aggression towards other people increases even at relatively low noise levels. Noise and vibrations cause problems with sleep, which in turn leads to a reduction in working performance.

Data has indicated that persons disturbed by noise and vibrations are incapable of deep sleep. Recent data have shown that the growth of children is restricted by reduced body production of growth hormones.

Vibrations also create problems with premature ageing and decay of buildings (settling, alligator cracking and similar damage). Many experts consider that this is a neglected problem area and that extensive needs for repairs will arise in the near future. In addition, vibrations cause problems through disturbance to sensitive instruments and computers. At present, there is a requirement on many computers (disk storages are especially sensitive) that they should not be exposed to accelerations in excess of 1 m/s².

Further research is necessary in order to quantify the size of this problem, which in particular concerns urban areas.
8 MEASURING STRUCTURAL CONDITION

The elastic deformation (deflection) of the road in dynamic loading is internationally the most common structural condition parameter and in Sweden the only one currently used for determining structural condition. Research should therefore be directed primarily at further development of the falling weight method, even if other methods, such as the wave propagation method, may be considered. The development of the falling weight method should include both the development of an evaluation model for paved roads based on the measurements obtained today, i.e. the deflection at 2 points, and also a study of the possibilities of a more detailed analysis of the structural condition (determination of the mechanical properties of various material layers), for example, by recording surface deflection at several points with falling weight measurements.

The measuring capacity using falling weight measurements is comparatively low, which makes the method less suitable for larger surveys. The study of possibilities for making general deflection measurements at normal traffic speeds, e.g. with the aid of laser technology and loading with rolling wheels is therefore an urgent research task. In the US research has been in progress for several years to develop this technique. After seeing the VTI's Laser RST (see Section 9) earnest requests have been received from the US to start collaboration. The VTI has examined the problem of performing rapid measurements of deflection with laser technology and has tentatively stated that it should be possible to solve the problems involved by using two "Laser RST rakes". One rake measures the undisturbed road surface and the other measures the road surface influenced/deformed by the vehicle.

If it is found that the development of quick methods for measuring bearing capacity is more difficult and demands more resources than expected, the possibility remains of measuring road surface condition in order to localize the road sections where the need for bearing capacity measurement is greatest. As mentioned in Section 9, fast, integrated measurement systems have been developed for this type of measurement. Opinion on the prospects of using this approach is divided among researchers. However, the idea appears so interesting that it should be investigated in greater depth.
MEASURING ROAD SURFACE CONDITION

Since functional requirements on the road surface have begun to be emphasized, there is an increased need for objective measurement and regular follow-up studies of functional changes. Research and development of measuring methods have therefore been given greater priority than previously. It is important that the new measuring methods now being developed meet the following requirements:

1. **Validity**, i.e. the instrument must measure what it is intended to measure. This must be checked experimentally with statistical analyses and logical deduction.

2. **Reliability**, i.e. the measuring method must give the same results in repeated measurements.

3. **Traffic safety**, i.e. measurement must not expose personnel and road users to increased risks.

4. **Handling**, i.e. the measuring instrument must be easy to use and repair if faults occur. Data must be presented so that they can be evaluated directly and also stored directly in a computer.

5. **Capacity**, i.e. the equipment must make measurements rapidly. Personnel costs are increasing continuously and will dominate measurement costs on a given section or road, even where expensive measuring instruments are used.

The measuring system and the system for follow-up also include storage and handling of acquired data. With today's rapidly increasing data processing resources, handling data may be regarded as a trivial problem. However, a storage system where all the data is stored and made continuously accessible seldom works properly. A continuous review of what is to be stored and made accessible is therefore necessary. Representatives of road administrators and research institutions should collaborate with programmers and systems analysts in solving this problem. The variables to be measured and stored, and information on where and how
they are to be measured, should be governed to an increasing extent by the
decision models and strategies discussed earlier (see Section 4) and which
are now taking shape. Research into what can be measured and what this
will cost should be carried out to produce a basis for decisions on what is to
be measured, i.e. a compromise between the need for knowledge and what
is economically and technically reasonable.

One often ignored question in conjunction with measurement is the
adaption of measurement to needs. A major road network where intensive
traffic rapidly affects the road surface requires frequent measurement, not
only to study the changes as such but primarily in view of the high road
user costs that deterioration of these road surfaces can lead to.

The condition variables mentioned below include road surface roughness,
cross-profile, friction, texture and light reflection. The VTI has been
studying these road surface properties for many years, in addition to
developing methods for measuring the properties and studying questions of
the consequences of measuring indexes, especially for the road user. The
experience gained can provide a basis for discussions regarding further
research and development in the various sub-areas defined by the above
condition variables. The predicted research requirement regarding metho-
dological development in these sub-areas is described below.

9.1 Roughness

The measuring methods so far used at the VTI have all been of the response
type, i.e. the measuring index reflects the mechanical response in a
measuring vehicle travelling over the road surface. This response has in
one way or another been read off and a mean value calculated for a
selected measuring section. Roughness measurements of this type have
proved to give good prediction of peoples' sensation of comfort when
travelling in different types of vehicles on roads with different degrees of
roughness.

To be able to make more detailed studies, primarily of the influence of
road roughness on vehicle and goods damage, equipment is required for
measuring and recording the longitudinal profile of the road, which can then be analysed with regard to wavelength and amplitude components. The development of such equipment is in progress at the VTI but there is a need to develop the technique further for better measuring precision and improved administrative routines.

This type of data is also required in validating and further developing models for the change in road surface condition as described in Section 5.

9.2 Cross-profile

Very high accuracy is required in determining abrasion/wear with cross-profile measurement. Wear measurement with the equipment currently used in the field is timeconsuming. Development of a profilometer utilizing, for example laser technology, appears necessary if reliable and quick measurements are to be possible in future. It should be possible to use the profilometer on pavements with varying texture (from coarse surface dressing to smooth asphalt concrete).

Cross-profile measuring systems can be divided into two main types, one which is intended for measuring an individual cross-profile at a selected point along the road and one which is intended for continuous measurement while driving, with subsequent calculation of the mean profile for the measured section of road.

The latest example of a cross-profile measuring system of the first mentioned type is the Primal system developed at the VTI. This uses a laser beam aimed across the road to guide a small vehicle which measures the cross-profile having the laser beam as a reference. The measured cross-profile can then be illustrated with the aid of a printer and also used to calculate rut depth, rut infill volumes etc.

Examples of the second type of cross-profile measuring system are the Saab Road Surface Tester (RST) and the VTI Laser RST. The Saab RST uses 26 rearward aimed sensing arms on wheels following the road surface and mounted on a 2.5 m long beam across the front of a Saab 900 car. This gives a measuring width of 2.5 m and a lateral resolution of 0.1 m.
The VTI Laser RST uses eleven lasers mounted in a similar way on a 2.5 m long beam. Since the two outermost lasers are angled 45° outwards, measuring width is increased to 3.1 m with an average lateral resolution of 0.31 m. The number of lasers has proved to be optimal; fewer would give unsatisfactory reproduction of the profile and more would increase costs without notably improving the measuring results. In exceptional cases, e.g. in ruts with very steep edges where the driver does not not drive in the ruts, the greatest depth may occur between two lasers.

Another problem specific to Sweden occurs where the hard shoulder is used more or less a driving lane. Instead of 3.75 m lane width, the width to be measured is about 5 m, which often causes large errors with a 3.1 m wide cross-profile measuring system.

In both the Saab and VTI Laser RST the measured cross-profile is used for calculating mean profile, mean of the maximum rut depths and rut infill volumes. Stationary measurements permit direct comparison with Primal.

No further development of cross-profile measuring system is considered necessary in order to relate cross-profile data to relevant traffic effects. However, it is possible that integrated measures such as the mean of maximum rut depths etc must be extended with others.

Finally, it is desirable to be able to measure and analyse the cross-profile in such a way that an effective validation is obtained of the models for development in pavement surface condition as described in Section 5. Interesting data in this context are the distance between rut floors, rut depths in inner and outer ruts, rut width, rut shape etc. A certain development of evaluation routines is probably necessary for this purpose.

9.3 Crossfall

The crossfall or lateral inclination of a road can be measured stationary or from a moving vehicle.
Stationary measurement can be carried out with levelling or with an inclinometer. An inclinometer is included in the Primal profilometer described in the previous section, which allows the measuring reference, the laser beam and thus the cross-profile to be related to the horizon. The crossfall can then be determined, for example, as the angle between the regression line through the cross-profile and the horizon.

The Saab RST is provided with a gyro system allowing calculation in a similar way of the crossfall as defined above. Calculation takes place continuously while driving, whereupon the measured crossfall is directly compared with a list of standardized crossfalls stored in the computer in the measuring vehicle. The results are printed out in the form of deviations from the standard. To select a standardized crossfall from the list, information is required on the displayed speed limit for the road, entered by the driver into the computer, and on the radius of the curve which is calculated continuously from the vehicle's speed and lateral acceleration, the latter being measured with an accelerometer mounted in the vehicle.

A method for crossfall measurement is also planned for installation in the VTI Laser RST. This uses an inclinometer mounted on the beam on the cross-profile measuring vehicle carrying the lasers. It can be used for stationary measurement while driving at a speed not exceeding 10 km/h. In cornering at higher speeds the inclinometer gives incorrect results owing to the influence of lateral acceleration. However, it is theoretically possible to compensate for this error. Two methods for this will be studied. If this approach does not prove successful, crossfall measurement with a gyro will be introduced in the measuring system.

Knowledge of both the crossfall and cross-profile of a road makes it possible to calculate not only the above-mentioned rut infill volumes but also the volumes required to restore the road surface to standard crossfall and to calculate the theoretically greatest depth of water in the ruts, which can be used as a criterion in deciding on action to improve traffic safety.
9.4  Friction

The method used so far at the VTI for measuring friction, the Skiddometer principle, is considered satisfactory and requires no further development. Nor is it intended to replace this method by any other.

The method, which has been developed by the predecessor to the VTI, the National Road Institute, (SVI) is based on a measuring wheel being braked so that the wheel rotates with a certain specified slip relative to a freely rotating wheel at the same road speed. The slip value is in principle chosen so that the maximum friction force is obtained for the particular combination of measuring tyre and road surface. The friction force is measured and used together with the known load on the measuring wheel to calculate the friction coefficient of the road surface.

Over the years, the skiddometer principle has been used in the design of a number of types of friction measuring vehicle, of which BV11 has achieved the most widespread use. Unlike other designs of both earlier and later dates, BV11 has a measuring wheel size of 4.00-8" which differs from normal car wheels. The same measuring principle and wheel dimension have been used in the Saab Friction Tester and Saab RST measuring cars.

Even if no further development of the measuring system is necessary, relatively extensive evaluation is required especially for those measuring systems using the smaller wheel dimension. A small, light measuring wheel means light, inexpensive and relatively uncomplicated measuring equipment. However, it has not been fully investigated whether a small measuring wheel corresponds to a normalsize car wheel with regard to the friction measuring values. An experimental study of this aspect should therefore be made.

For all measuring systems it is not fully known how the measured friction value should be converted to braking effect for a car or how friction should be measured so that it corresponds to the friction a driver/vehicle can utilize both in normal and surprise situations. A study of this problem consisting of theoretical and experimental sections should be carried out.
9.5 Texture

In the VTI Laser RST project a mobile macrotexture measuring system has been developed, which measures the road surface profile with the aid of a laser beam. A special simplified version has been adapted for use in the Laser RST car. This simplified version operates satisfactorily at 70 km/h. At present, the measurement is carried out with 4 laser units mounted on the Laser RST being tested in the USA. The system is planned for use in a "Pavement Management System" at the end of 1984. In the American system the laser units also record cracks in the road surface.

The same principle as is used in the macrotexture measuring system should be applicable in a future microtexture measuring system.

Microtexture influences friction and probably also tyre wear. To be able to predict these values on the basis of non-contact measurement with the VTI Laser RST, a microtexture measuring system must be developed. This may in principle consist of the non-contact position sensor as described above, but with a considerably smaller light spot. The light spot size must be reduced to 0.1-0.2 mm to be able to measure wavelengths down to 0.2-0.4 mm. In actual fact, the microtexture covers a larger area (shorter wavelengths) but wavelengths of 0.2-1.0 mm have proved to be very significant. An American study has shown that this wavelength range is the most interesting, i.e. it has the highest correlation with the friction coefficient.

It is not probable that this type of microtexture measurement can be used at normal vehicle speeds within the foreseeable future. Measurements must be made with the vehicle driven slowly (perhaps at 20 km/h) along those sections where microtexture is to be recorded. Those places where measurement is warranted (potential low friction section) can be indicated macrotexture measurement, which can take place continuously.

A non-contact, mobile microtexture measuring system would be able to rationalize considerably assessment of the friction properties of roads by providing better information on the relationship between surface microtexture and friction.
With access to the profile data of a road and knowing the enveloping properties of the car tyres it should be possible to detect and calculate relationships for tyre deformation due to surface coarseness. Also the resulting "draining" facilitated by surface coarseness (acting together with the tyre) should be predictable. It will then be possible to find better measures of determining how friction, aquaplaning risks, fuel consumption, tyre wear and noise are influenced by surface coarseness.

9.6 Light reflection

The specific luminance of the road surface is a physical expression of the light reflection properties of the road surface. The light reflection of a surface varies as a function of the angle of incidence of the light with the surface, the angle of the light and the internal relationship between these angles reflected. This can be visualized by considering a horizontal surface on the ground surrounded by a hemisphere. In this hemisphere there is a light source whose light is directed at the horizontal surface. The hemisphere also contains an instrument for measuring the light reflected from the illuminated surface. The light source and the measuring instrument can occupy any combination of positions in the sphere. Naturally, not all combinations are of interest in the traffic context. If the measuring instrument is replaced by the road user's eye, it is easy to understand that the specific luminance of a road surface is important in those combinations of incidental light on the road surface and reflected light in the road user's eye which occur in traffic.

Three special cases can be discerned here:

1. Retroreflection of the road surface

In this case, the road surface is illuminated by the driver's own headlights (in darkness) and is observed with the aid of light reflected from the road surface toward the driver's eyes.

In a joint project between the VTI and the Lighting Engineering Laboratory, LTL, of Denmark, basic measurements have been made systematically for
the first time on a number of road surfaces (sawn samples). The measurements have been documented in the "Mörkertrafik" series of publications (Rapport nr 4). The results will provide a basis for designing a measuring instrument. International standardization of the measuring method is being sought. The consequences of retroreflection for detecting obstacles have been reported in VTI Rapport 202. A study of visibility on the road varies with road surface retroreflection remains to be performed.

2. Reflection on the road surface

In this case traffic is travelling towards a setting sun or meeting a vehicle in darkness. The incidental light towards the road surface from the sun or from an oncoming vehicle's headlights is reflected to a greater or lesser degree from the road surface towards a driver. A road surface with a high degree of reflection may cause dazzling in such situations.

Practically no research has been done in this area. First, it is necessary to develop the method for measuring reflection of a road surface. Finely textured road surfaces have the highest reflection. Here, wet conditions are a serious problem from the research aspect since these conditions are instable and change rapidly.

When measuring methods have been developed it will be necessary to examine how the existing variation in reflection between different road surfaces affects visual conditions in night traffic (i.e. measurement of the sight distance to an obstacle and measurement of visibility of the road).

At present, a project supported by the Swedish National Road Administration is in progress with the aim of studying methods of measuring reflection and its consequences for drivers in darkness.

3. Road surface reflection in road lighting and daylight.

Light from road lighting installations has a relatively small angle of incidence with the road surface but is seen by the road user at greater angles than the normal. This is similar also to most daylight situations.
For many years the VTI has supported the LTL in this area of research. The LTL has developed excellent measuring methods and prediction models for describing the luminance (level and evenness) of the road surface in various types of lighting installation, road surfaces and road conditions (dry and wet respectively). Here there is a great need to develop behavioural science methods for evaluating visual conditions in different installations. The Swedish National Road Administration is supporting a project with this aim at the VTI but work has so far been slow, owing to a shortage of personnel in the area of perceptual psychology.
10. TRAFFIC MEASUREMENT AND PROGNOSIS

10.1 Heavy traffic/axle loads

There is no doubt that the volume and composition of heavy traffic is of decisive significance in the disintegration of roads. Consequently, a condition for optimizing road maintenance is the ability to estimate actual traffic loads, both current and future with regard to different traffic compositions, roads and areas of the country.

The aim of research in this area should therefore be a model which can convert composite information on traffic, geographical location and type of road to a measure of traffic relevant from the aspect of structural disintegration, for example the equivalent number of 10-ton axles ($N_{10}$). To achieve this, current programs for axle load measurement should be extended. At the request of the National Road Administration, the VTI is engaged in making axle load measurements with recording equipment which is moved between 5 fixed measuring sections (one year's measurements at each). The VTI is also making measurements with its own equipment in one section. An extension of the program for axle load measurements will probably be limited owing to the relatively high cost of equipment. An urgent need is thus the development of a simpler type of equipment and to use this in complementing the axle load measurements. Work is in progress to study the possibility of using visual observations of vehicle types to estimate $N_{10}$ with acceptable precision.

There is also a need to facilitate the making of prognoses of the future development of heavy traffic and changes in the distribution on different axle loads.

10.2 Studded tyres

Abrasion of the road pavement is determined by the volume of traffic using studded tyres and by the aggressiveness of individual studded tyres to the road surface. Regulations governing the design of studded tyres and their use were introduced during the 70's and these may be revised in the near
future. Regulations and development in studded tyre technology have led to a reduction in wear from these tyres. It is well known that studded tyres on heavy vehicles wear the road pavement considerably more than studded tyres on cars.

The proportion of vehicles with studded tyres has increased in recent years. This applies both to heavy and light vehicles.

Prognoses for future wear from studded tyres are important components in a model for optimizing pavement maintenance. The information required is:

1. Traffic mileage for heavy and light vehicles with studded tyres.
2. The specific wear from heavy and light vehicles with studded tyres.

To obtain this information, a follow-up study is necessary of the proportion of vehicles with studded tyres in different parts of the country, the condition of the studs and a follow-up of the way in which tyres are studded. A suitable investigation method is spot checks in conjunction with annual vehicle inspections. Another suitable method may be a questionnaire directed to a sample of Swedish vehicle owners.

To study the resistance to wear in pavements on for example test roads, the number of vehicles with studded tyres has so far been counted manually at randomly chosen times during the season when studded tyres are used. The possibility of developing a method which allows automatic recording of the number of vehicles with studded tyres should be examined. Continuously counting of the number of vehicles with studded tyres combined with wear measurements on a representative selection of the country's roads would provide the best basis for calculating the development in wear.
11. EVALUATION OF EFFECTS

Extensive research and investigative work has been done to determine usable values/measures of time and accidents. The values/measures used by the Swedish National Road Administration in its calculations of traffic economics are relatively widely accepted and no further research in this area is considered necessary.

In the case of vehicle costs, there are no great problems regarding evaluation. The problem is to obtain statistically representative data for the traffic exposed to influence from the pavement surface.

However, no generally accepted methods for evaluating road user comfort have yet been found. Since comfort should be included in an optimization model, it is necessary that research be started in order to find appropriate methods. A serious weakness in this context is the isolation of comfort from other effects such as safety and the risk of damage to the vehicle. Certain proposals for making an evaluation of comfort are given in Section 11.1.

External noise and vibrations must also be evaluable. Research as described in Section 11.2 is needed also here.

If the entire need for information as outlined in this proposal were to be satisfied before being able to design systems for optimizing pavement maintenance, no such systems might ever be ready for use. Some of the research problems are so difficult that they will take a very long time to solve. In awaiting the results of the long-term research projects, the available information must be used in the best way possible. Purely practically, this means rating the various defects of the pavement in a way that reflects their relative importance to traffic and continued deterioration of the road. Often, too little attention is devoted to this aspect of research. However, there are methods where existing (if deficient) knowledges of the relative significance of pavement properties can be put to use in a more effective way. This is especially important since this evaluation may be of great significance in deciding the priority of different surfacing strategies.
A method for making such a relative evaluation of various defects of the pavement surface is described in Section 11.3.

11.1 Evaluation of comfort

Certain initial studies of road user's willingness to pay for smoother roads have been made by the VTI. Those participating in the study of comfort assessment were asked how great an increase in the price of petrol they were prepared to accept in exchange for improved road smoothness. This method has two weaknesses. The first is that it does not define comfort. The replies may depend on the idea people have of the effect of road roughness on vehicle wear, risk of accidents etc. The second weakness is that those questioned might possibly show less willingness to pay if they were actually forced to pay.

Comfort evaluation is closely connected with evaluation of journey time. Journey time cost is the product of journey time and the time value. It is not unlikely that the time value depends on the pavement standard. This question has been examined deeper in a joint Nordic project financed by the NÄT (Nordic Governmental Committee for Transport Questions). The project includes a discussion of the possibility of studying road users' choice of roads and how this depends on pavement standard. Analysis of the data may lead to a more relevant evaluation of comfort. It is possible that this will result in the need to use different time values for different comfort levels, instead of making a direct evaluation of these.

In the concept of comfort we have also included internal vehicle noise. It is important that this also can be evaluated. A possible method may be to isolate those costs incurred by car manufacturers in suppressing noise from the various parts of the vehicle and to derive a relationship between internal vehicle noise and costs. This type of analysis may also be of value in the case of vibrations.
11.2 Evaluation of external noise and vibrations

The evaluation to be made regarding external noise depends partly on how many people are exposed to disturbance by noise and partly on the degree of the disturbance. In its methodology report, "Assessing the urgency of road and street building projects", the Swedish National Road Administration has produced a method for an evaluation of this type. The method is based on studies of how property prices are influenced by traffic noise.

The first phase should be based on the evaluation made by the Swedish National Road Administration. However, further research is urgent. This applies especially to municipalities where it may be found that the use of opengraded/porous pavements, which have extremely low noise levels, is very profitable on certain streets and roads even if maintenance costs are found to increase.

Section 7 mentions the effects of vibrations on humans, buildings and sensitive instruments. No methods exist for evaluating these effects. Research in this area is vital.

11.3 Systematized evaluation methods based on the accumulated experience of researchers, decisionmakers and technical personnel

Research based on data analyses and experiments has gradually increased our knowledge of the consequences of road surface properties for the road user, road keeper and environment.

However, much work remains before these consequences can be analysed and converted to costs. One approach will then be to use all relationships available, even if these are very uncertain, and make calculations in various models. Unfortunately, this often leads to very poor results which often, are used uncritically, despite the warnings of model designers regarding the great uncertainty of the input data. A variant of this is to select subjectively the data which can be "believed in", often with the effect that the model becomes subjectively coloured. In principle, anything can be proved or any process governed according to what was
believed at the outset. Often, these two types are mixed in model design and no information is given on the choice of input data.

Despite these problems, evaluation models have to be produced in order to be able to assess the need for action and research. However, there are considerably better methods for avoiding the error sources mentioned. To return to the need for input data, cost relationships are required for all variables. There are a number of studies and investigations, which can be more or less relied upon, and a large amount of practical knowledge of these variables, in addition to views on variables for which no cost relationships have been studied.

To achieve as reliable input data as possible for the models, use should be made of all the knowledge previously gained. Instead of applying the choice and opinion of an individual model designer, different groups should be used who collaborate and make choices, for example, with the aid of the so called Delphi method. With this method a number of people are appointed representing decision-makers, technical personnel and researchers, who are allowed to penetrate all the information in the area. The group then conducts discussions to reach as unanimous an opinion as possible on what is credible and important among the available basic information. In the type of research considered here, the group proceeds to formulate probable cost relationships for the variables of interest. The opinions are collated and discussed in smaller groups, some of which are homogeneous and some heterogeneous with regard to the background of the assessors. A final verdict is then made, which is used as input data to the model. The input data is thoroughly penetrated, weaknesses in the investigations pointed out, neglected relationships taken up and individuals' subjective assessments minimized through the different backgrounds of the groups and their members.

A condition for a successful assessment is that presentations of knowledge be made in an easily understood and objective way and that summaries be made in advance. It is also important that uncertainty of the knowledge be reported.
12. CONCLUSIONS AND RECOMMENDATIONS

The description given in the previous chapter shows that extensive research is needed to be able to apply systems for socio-economic optimization of pavement maintenance. The most important gaps in knowledge are at present considered to be:

1. Methods/models for predicting long-term changes in road/road surface condition when implementing various surfacing strategies.

2. Effective methods for measuring the structural condition (bearing capacity) of roads.


4. The influence of pavement surface condition on vehicle wear.

5. The influence of pavement surface condition on traffic accidents.

6. Evaluation of effects.

As shown in certain respects in Sections 4 and 11, the results of research should not be awaited before beginning to design the systems. There is already sufficient knowledge to begin research on the systems side. However, it is important that the systems be given such a flexible structure that new and more reliable knowledge can be introduced as research continues. The advantage of this method is that the need for new research is governed the whole time by application aspects. Since the condition of the pavements, can be followed up as a result of new, fast measuring methods, continuous feedback can be obtained where the models describing pavement performance of the road can be validated. The "traditional" research into pavement technology will thereby be complemented and partly replaced by research with a more statistical orientation.

Section 4 mentions that it is not probable that there is one pavement maintenance system suiting all road administrators in Sweden. It may well
be that the Swedish National Road Administration requires one system and the municipalities another, according to the different resources they possess or can obtain for measurement and follow-up work.

At the request of the Swedish Transport Research Delegation (TFD), now the Swedish Transport Research Board (TFB), a committee has been appointed with the task of surveying and summarizing the need for research in the entire area of road and street operation. The committee was also asked to propose and assign priority to the TFD's further research into road and street operation on the basis of this requirements analysis. The VTI has acted as investigator for the committee and has reported on the work done in VTI Meddelande 328. The report states that in Sweden there are about twenty organizations which are involved in different ways in research into operation and maintenance of roads. At the proposal of the committee the TFD decided in spring 1984 to grant research funds for more detailed planning and programming of further research in six sub-areas, two of which deal with questions coinciding with points 1 and 3 above.

Since questions concerning pavement maintenance are and will continue to be of central importance for the VTI, we propose that two groups be formed within the VTI (one for the Swedish National Road Administration and one for the municipalities) with the task of developing suitable systems for socio-economic optimization of pavement maintenance. In addition to contacts with the TFB's operation research committee, it appears appropriate that the "Municipality group's" work be coordinated with the continued work of the operating cost committee. The groups should naturally include road keepers in the first instance. However it is important that researchers from the VTI and other research bodies working in this area also be included. This will allow research to be better coordinated than at present and, as mentioned previously, to have a more applicable orientation.

Finally it is important that the groups be allocated resources for systems development and research so that they do not simply constitute consultative groups. Their duty is to actually develop systems which can be implemented in pavement maintenance.
It is also essential that collaboration takes place between the Swedish National Road Administration group and the municipality group since many of the problems are similar and can probably be solved jointly.
LITERATURE

"The AASHO Road Test".

Abel R:
"Economics of staged construction of flexible road pavements".
Transport and Road Research Laboratory, TRRL, report 1069, Crowthorne 1983.

Alm L-O:
"Mätning av vägbeläggningars makrotextur för friktionsbestämning. Principer och mätmetoder."

Arnberg P W, Carlsson G och Magnusson G:
"Inverkan av vägjämnheter. En problemanalys".
Statens väg- och trafikinstitut, VTI Meddelande 95, Linköping 1978.

Arnberg P W och Sjögren L:
"Nordiska friktionsmätare. En jämförande studie".

Arnberg P W och Åström G:
"Vägjämnheters inverkan på bilförarens prestation och trötthet. En litteraturgenomgång och ett simulatorexperiment".

Backman C:
"Slitage av bildäck på olika vägtytor – en jämförelse mellan körningar på en ytbehandling och en asfaltbetong".
Statens väg- och trafikinstitut, VTI Meddelande 130, Linköping 1978.

Björketun U:
"Samband mellan vägbeläggningar, väderlek och trafikolyckor 1977".

Björklund A:
"Creep induced behaviour of resurfaced pavements. Some studies with the aid of beams subjected to a temperature wave and loaded under plane strain conditions".

Brodin A:
"Statistik över fordonsskador. Jämförelse mellan olika statistikkällor samt beskrivning av risktal. En förundersökning".

Butler B C, de Carvalho J T and Hudson W R:
"Relating Vehicle Operating Costs to Low Volume Road Parameters in Brazil".
Transportation Research Record 702, 1979.
Carlsson G:
"Effekter av driftåtgärder. Planprojekt".
Statens väg- och trafikinstitut, VTI Meddelande 81, Linköping 1978.

Carlsson G:
"Ytbehandling av grusvägar. Uppföljning av friktion, hastigheter och sidolägen efter ett år".

Carlsson G:
"Spårbildningens inverkan på trafikens säkerhet. Planprojekt".

Carlsson G och Öberg G:
"Ytbehandling av grusvägar. Trafik- och friktionsstudier".

Dean E H:
"Relationship of the Tire-Pavement Interface to Traffic Accidents Occurring under Wet Conditions".
Texas Highway Department 1969.

Driftkostnadsutredningen:
"Gator och vägar. Huvudrapport 1981".
Kommunförbundet och driftkostnadsutredningen 1982.

Gynnerstedt G:
"Värdering av vägens tillstånd och åtgärdsbehov. En systemanalytisk modellskiss".

Hammarström U och Ericsson T:
"Samband mellan fordonskostnader och väg- och trafikmiljö. Litteraturstudier".

Hammarström U och Karlsson B:
"Fordonskostnader. En datoriserade beräkningsmodell för fordonskostnaders beroende av väg- och gatumiljö".

Hammarström U och Karlsson B:
"Samband mellan fordonskostnader och vägstandardmått. En analys av Televerkets fordonsservice".

Hide H, Abaynayaha S W, Sayer I and Wyatt R J:
"The Kenya Road Transport Cost Study. Research Vehicle Operating Costs".
Transport and Road Research Laboratory, TRRL, report 672, Crowthorne 1975.

Hultqvist B-Å:
"Beläggningsunderhåll baserat på maskinjusteringar".
Jansson H:

Jansson J O, Carlsson G och Hammarström U:
"Program för forskning om sambandet mellan trafikantkostnaderna och vägtyans egenskaper".

Jönsson J och Nilsson P:
"Recycling - framtidens beläggningsunderhåll".

Kennedy C.K and Lister N.W.:
"Prediction of pavement performance and the design of overlays".
Transport and Road Research Laboratory, TRRL, report 833, Crowthorne 1978.

Kihlgren B:
"Slitage av bildäck vid körning på äldre ytbehandling och asfaltbetong".

Kolsrud B och Nilsson G K:
"Samband mellan vägtya och reshastighet. Etapp 2. Jämförslrelser mellan ytbehandling och massabeläggning".
Statens väg- och trafikinstitut, VTI Meddelande 277, Linköping 1981.

Kolsrud B och Nilsson G K:
"Beläggning av grusvägar med YTG - effektstudier 1978-80".

Linderoth U:
"Samband mellan vägtya och reshastighet. Etapp 1. Beläggningsunderhåll på hårt slitna vägar".

Magnusson G och Arnberg P W:
"Vägojämnheters inverkan på bilars broms- och styrbarhet. En litteraturstudie".

Magnusson G, Arnberg P W och Pettersson H-E:
"Måttning och bedömning av ojämnheter på grusväg".

Magnusson G, Carlsson H-E och Ohlsson E:
"Inverkan av tunga fordons fjädringsegenskaper och däckutrustning på vägens nedbrytning".

Nordiska vägtekniska förbundet:
"Projekt inom vägunderhållet 1976".

VTI MEDDELANDE 406 A
Nordiska vägtekniska förbundet:

Nordiska vägtekniska förbundet:

Nordiska vägtekniska förbundet:

Nordiska vägtekniska förbundet:

Odsell O och Laurell H:
"Möjliga bränslebesparingar med befintliga personbilar".

Ohlsson E och Rosengren Å:
"Vägslitage och bromsverkan. Provning av en ny däckdubb för personbilar".

Olofsson G:
"Bränsleförbrukningens beroende av olika väglagsförhållanden".

Olofsson G:
"Bränsleförbrukningens beroende av beläggningens typ. En pilotstudie".

Rizenbergs L, Burchett J L and Warren L A:
"Relation of Accidents and Pavement Friction on Rural, Two-lane Roads".

Sandberg U:
"Tire/Road Noise on an Open-Grade Friction Course".

Sandberg U och Ejsmont J A:
"Review of Comparative Studies of Tire/Road Noise Measurements on Drums and Roads".

Sandberg U och Lundquist S-O:
"Externt däckbuller på vägbeläggningar av typ enkel och dubbel ytbehandling".

Sandberg U och Lundquist S-O:
"Vägbeläggningens inverkan på bullret i personbilar. En förstudie".
Schandersson R:  
"Samband mellan vägbeläggningar och trafikolyckor 1977". 

Schandersson R, Simonsson B och Thunberg B:  
"Forskning om drift av gator och vägar. Kunskapsöversikt och FoU-behov". 
Statens väg- och trafikinstitut, VTI Meddelande 328, Linköping 1983.

Skjoldby A:  
"Bilres energiforbruk och slidlag". 
Statens vejlaboratorium, interne notater 110, Danmark.

Statens väg- och trafikinstitut:  
"Forskardagar - vägtransporter del 2. Rapportsammanställning av föredrag vid forskardagarna i Linköping 1984-01-10--11 beträffande - trafiksäkerhet - trafikmedicin - trafikteknik - fordonsteknik - vägars drift och underhåll". 

Statens vägverk:  
"Beläggningsinventering 1980". 
Driftsektionen DD 131, Borlänge 1980.

Statens vägverk:  
"Femårssplan drift 1982-86. Verksamhetsplan". 
Driftsektionen DD 130, Borlänge 1981.

Statens vägverk:  
"Femårssplan drift 1982-86. Service- och underhållsåtgärder". 
Driftsektionen DD 134, Borlänge 1981.

Statens vägverk:  
"Femårssplan drift 1982-86. Fördelningsmodeller". 
Driftsektionen DD 135, Borlänge 1981.

Statens vägverk:  
"Beläggningsinventering 1982". 
Driftsektoinen DD 131, Borlänge 1982.

Statens vägverk:  
"Beläggningsinventering 1983". 
Driftsektionen DD 131, Borlänge 1983.

Statens vägverk:  
"Återanvändningsmetoden" 

Statens vägverk:  
"Recycling av asfaltmassa". 
DDa-rapport 81109-25, Borlänge 1981.
Statens vägverk:
"Lagning och underhåll av beläggningar".
DDa-rapport 81118-25, Borlänge 1981.

Statens vägverk:
"Ytbehandling i två lager (Y2)"
DDa-rapport 81505-25, Borlänge 1981.

Statens vägverk:
"Tillverkning och utläggning av asfaltemulsionsbetong (AEB)"
DDa-rapport 81609-25, Borlänge 1981.

Statens vägverk:
"Heating"
DDa-rapport 82401-25, Borlänge 1982.

Statens vägverk:
"Angelägenhetsbedömning av väg- och gatubyggnadsobjekt. 3. Effekt-
katalog"

Statens vägverk:
"Effekter av driftåtgärder"

Statens vägverk:
"Användningen av dubbdäck vintern 1979/80"
PP-meddelande 12, Borlänge 1980:12.

Statens vägverk:
"Effektkatalog. Service- och underhållsåtgärder"
P-rapport 17, Borlänge 1983.

Statens vägverk:
"Dubbdäck. Utredning av möjligheterna att minska beläggningsslitaget
från dubbdäck"

Styrelsen för teknisk utveckling:
"Däck/vägbana - en bullerkälla i trafiken"
STU-info 175, Stockholm 1981.

Sävenhed H:
"Samband mellan vägyska och bränsleförbrukning. Jämförelse mellan ytbe-
handling och massabeläggning"

Transportation Research Board, National Academy of Science:
"Low-Volume Roads: Second International Conference"

Transportation Research Board, National Academy of Science:
"Pavement Management and Rehabilitation of Portland Cement Concrete
Pavements"
Transportation Research Board, National Academy of Science: 
"Pavement Management". 

Transportforskningsdelegationen: 
"Dubbdäck". 

Wallman C-G: 
"Energiförbrukning vid drift av vägar och gator. Program för FoU-arbeten". 
Chalmers tekniska högskola, rapport 38, Göteborg 1982.

Wellemann A G: 
"Water Nuisance and Road Safety". 
SWOV, Voorburg, Nederländerna 1978.

Zipkes E: 
"Veränderung der Struktur von Strassen ober fläcken und ihr Einfluss auf Unfallraten". 