The significance of various road surface properties for traffic and surroundings

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Foreword

The Swedish National Road and Transport Research Institute (VTI) has been commissioned by the Swedish National Road Administration to carry out a project entitled "The impact of road surfaces on traffic". The aim is to develop improved traffic impact models for the Swedish National Road Administration's Pavement Management System (PMS).

The director of the project is Anita Ihs and Johan Lang and Jaro Potucek are the contacts at the National Road Administration. This report is a revision of previous evaluations of the significance of various road surface properties for road-users and the surroundings made by an internal work group at VTI and presented in VTI notat 21-93. The revision has been carried out by the undersigned with the help of other project members. Georg Magnusson has been responsible for Appendix 1.

Anita Ihs
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Summary

The importance of the characteristics of the pavement surface for traffic and the environment – revision of state of the art report

By commission of the Swedish Road Administration, VTI is now engaged on a project entitled "Traffic effects of the road surface" with the aim of producing improved traffic effect models for the PMS (??) of the Road Administration and the Catalogue of Environmental Effects. Several subprojects are in progress to investigate the influence of the road surface on e.g. traffic safety, vehicle speed, vehicle costs and comfort.

As part of planning the work in the project "Traffic effects of the road surface", a revision has been carried out of VTI notat 21-93: The importance of different characteristics of the pavement surface for traffic and the environment.

An internal working group at VTI met a number of times in the spring of 1993 to discuss relationships between the state of the pavement surface and its consequences on traffic and the environment. The conclusions of these discussions are summed up in VTI notat 21-93, and represent the views of the working group regarding the state of knowledge prevailing at that time. A schedule was also drawn up concerning the importance of different properties of the pavement surface for road users and the environment.

Revision and amplification of this state of the art report, which is described in this note, has been carried out with the help of others involved in the project "Traffic effects of the road surface"
1 Background

In 1998 the Swedish National Road and Transport Research Institute (VTI) was commissioned by the Swedish National Road Administration (SNRA) to examine the traffic impact models in the latter's pavement management system for the maintenance of paved roads, PMS. VTI was also requested to make comparisons using the models and structure used in the World Bank equivalent HDM-4.

It was found that the documentation of how the models had been developed, of the hypotheses that had been made and of the studies on which they were based was insufficient. Against this background, and in consultation with the SNRA, VTI drew up a plan for continuing the work of improving and supplementing the existing traffic impact models in PMS.

1999 saw the launch of the main project, "The impact of the road surface on traffic" which comprised several subprojects. Below is a table of the subprojects carried out/ongoing in 1999 and 2000.

<table>
<thead>
<tr>
<th>1999</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Framework.</td>
<td>Framework.</td>
</tr>
<tr>
<td>The impact of road surfaces on safety.</td>
<td>Cont. Planning project. Simulator study of the impact of road surfaces on safety.</td>
</tr>
<tr>
<td>The impact of road surfaces on vehicle speed.</td>
<td>Planning project. Comfort study.</td>
</tr>
<tr>
<td>The impact of road surfaces on comfort.</td>
<td>The impact of road surfaces on fuel consumption and rolling friction.</td>
</tr>
<tr>
<td>Study of related literature.</td>
<td>Cont.</td>
</tr>
<tr>
<td>The impact of road surfaces on vehicle costs.</td>
<td>The impact of road surfaces on winter road maintenance.</td>
</tr>
<tr>
<td>The impact of road surfaces on noise properties.</td>
<td></td>
</tr>
</tbody>
</table>

Part of the aim of the subproject named "Framework" has been to establish a common framework for the various models describing how the road surface condition impacts on traffic. The project is also intended to set in motion, prepare, co-ordinate and prioritise individual subprojects.

As part of the "Framework" subproject, revisions have been made to VTI notat 21-93 (Schandersson, Magnusson, Wågberg & Öberg, 1993). An internal work group met at VTI in 1993 to discuss the connection between the condition of paved surfaces and the impact on road-users and the surroundings. In the report a table has been compiled of the significance of various road surface properties for road-users and the surroundings. This compilation of data has been revised with the assistance of other members of the main project and is presented in this report. Below is a brief description of the other subprojects.

In the subproject "The impact of road surfaces on accidents", the accident analysis is based on accidents reported by the police and data from measurements of surface conditions using Laser-RST. The criteria used in the analyses are rut depth and surface unevenness (IRI in mm/m). A previous study at the Institute, which was based on data.
from the end of the 80s (Sjölinder, Velin & Öberg, 1997), was more or less repeated in 1999 but this time with data from 1995-1998. The scope of the study was limited however, as was the earlier one, to include only those roads with AADT>1000. During the year 2000 the study has been extended to include the entire national road network i.e. also roads with AADT < 1000 and the years 1992-1998.

Even as concerns the subproject, "The impact of road surfaces on vehicle speed" the analyses are based on RST-data from 1992-1998. Speed data has been obtained from all the sites for continuous measurement of traffic flow and spot speed of the SNRA.

The comfort cost model used in the SNRA's PMS is based entirely, or in part, on a Finnish study of motorists' monetary evaluation of comfort from 1985. In 1999 a study was made of the literature available on this subject to establish whether or not there are any later models that can form the basis for a revision of the current model. The results of this study can be found in VTI notat 11-2000. (Forsberg & Magnusson, 2000). In brief, it was discovered that a large number of studies had been made of the connection between road unevenness/vibrations and the degree of comfort experienced. There were however very few studies where the aim was to set a price on the degree of comfort experienced or rather the lack of it.

Against this background, VTI was commissioned by the SNRA to plan the details of a comfort study during the year 2000 and then to implement it in 2001. At the request of the SNRA alternatives to the existing vehicle cost model in PMS were developed during autumn 1999 (Hammarström, 200). Available literature resources concerning the impact of road surfaces on fuel consumption, however, show very varying results. During the year 2000 therefore, VTI is therefore carrying out field studies to map the connection between fuel consumption and road surface and between rolling resistance and road surface. The results of the studies will also be used to validate the VETO model’s description of how resistance to motion varies according to road unevenness and macrotexture.

There is also an on-going project that focuses on the noise properties of road surfaces. One of the problems is to establish (quantify) the noise properties of paved surfaces. The aim of one part of the project is to develop a measuring method which will make it possible to measure these properties and which can be used to check that the various road projects are complying with stipulated environmental requirements (in this case noise requirements). Work has already started and is being carried out in collaboration with a great many other countries on a broad international front. A further problem, until better methods are found, is the ability to take into consideration the traffic noise emission in PMS as early as possible. A correction table for the noise properties of paved surfaces has been compiled within the project for this purpose.

Finally, the consequences of road surface conditions for winter road maintenance are also examined. The theory is that a rutted or uneven road surface impairs the effectiveness of ploughing and salting measures since the ploughshare makes less contact with ice and snow, and after salting has been completed there is more slush and water on the road surface. Ruts and unevenness in the road surface also increase wear and tear to the ploughshare.
2  The effects of road surface properties for road-users and the surroundings.

In the exposition below the relative significance of the various road surface properties is listed for each effect. The significance of the various road surface factors has been evaluated for each effect. This means that it is not the absolute significance or impact that is specified but the relative one.

2.1 Trafficability, travelling time

Trafficability and travelling time refer here to the impact of speed changes, driver behaviour during overtaking, tailbacks.

- **Significant impact:** Friction, longitudinal unevenness.
- **Moderate impact:** Rut depth and shape, megatexture, retroreflection, permeation to water.
- **Insignificant impact:** Crossfall
- **No impact:** Micro- and macrotexture, bearing capacity.

**Comments:** Micro- and macrotexture have great importance for friction and can thus be said (indirectly) to affect trafficability. Friction must however be regarded as the key parameter in this context. One reservation must however be made because the surfacing texture can have an impact on the noise level inside the vehicle and this in turn can have significance for the speed.

Increased variation in the megatexture reduces the speed level and consequently makes travelling time longer.

Rut depth, macrotexture and permeability to water are of significance for run-off /draining in the event of rain. Permeability to water here refers to the effect of open draining surfacing of the porous asphalt type or the like. Retroreflection is important for visibility especially when it is raining or it is dark.

**Background factors:** Alignment (curves) combined with surface damage caused by braking lead to reductions in speed.

Paved width and lane width affect the degree to which the traffic is rutbound and consequently the rut depth and shape.

Climate can indirectly have great impact because the frost process etc. affects longitudinal unevenness as well as other factors.
2.2 Road safety

Road safety here refers to traffic accidents and accident risk.

Significant impact: Friction

Moderate impact: Longitudinal unevenness, megatexture, retroreflection, permeability to water.

Insignificant impact: Rut depth, (and rut shape), crossfall.

No impact: Bearing capacity, macro- and microtexture.

Comments: The micro- and macrotexture have a significant impact on friction which in turn is regarded as the key parameter in terms of road safety impact.

Variations in transversal or longitudinal friction can lead to a greater accident risk e.g. during braking.

Macrotecture, megatexture, ruts and permeability to water impact on the depth of water on road surfaces and consequently on friction.

Studies have shown that ruts, generally speaking, have a rather insignificant impact on road safety. The tendency is, at least on dry roads, for ruts to have a certain positive effect. Under especially unfavourable conditions, when quantities of water collect in the ruts, there can be a risk for aquaplaning. Even if these types of accident are rare they can have serious consequences when the driver suddenly loses control of the vehicle. No empirical study of the significance of rut shape has yet been carried out. Part of the reason for this is that there are no accepted standards for defining rut shape. Furthermore, studies have shown that unevenness, in comparison with ruts, has a more significant and negative impact on road safety.

Correct crossfall should have insignificant impact on road safety. Incorrect crossfall in combination with bends should on the other hand have significant impact. Crossfall combined with ruts and water can also pose a special kind of problem.

Retroreflection probably has great significance in the case of wet road surfaces in the dark. The impact however, compared with friction, should be rather moderate.
Background factors: Alignment should have significance for road surface impact on traffic safety due to the fact that braking before bends followed by acceleration afterwards can give less friction.

Paved width and lane width affect rut depth and shape.

Climate generally and locally can in combination with road surface properties have significance for conditions turning slippery. The thermal properties of material further down in the road structure however are of probably greater significance. As has been previously mentioned, climate has an indirect impact on longitudinal and transversal surface unevenness due to its significance in the frost process.

2.3 Comfort
Comfort refers here to convenience, well-being and security in a broad sense, both in physical and mental terms.

Significant impact: Longitudinal unevenness, megatexture

Moderate impact: Rut depth and shape, macrotexture, friction, retroreflection, permeability to water

Insignificant impact: Crossfall

No impact: Microtexture, bearing capacity

Comments: Longitudinal unevenness and megatexture can cause vibrations and roll movements that impact negatively on comfort.

Crossfall should normally have insignificant impact. Incorrect crossfall in a bend would however reduce comfort. Variations in crossfall that cause roll movements can also reduce comfort.

Low friction can cause feelings of insecurity in the driver.

Macrotexture is significant for the level of noise inside the vehicle.

Retroreflection is significant for visibility, which in turn can be of significance for feelings of insecurity arising in the driver.

Significant levels of permeability to water reduce the amount of water on the road and boost driver confidence.
Background factors: Alignment, paved width and lane width can affect how the road surface develops and consequently, indirectly, comfort.

2.4 Vehicle wear

Significant impact: Longitudinal unevenness, megatexture.

Moderate impact: -

Insignificant impact: Rut depth and shape, macrotexture, crossfall

No impact: Microtexture, friction, retroreflection, permeability to water, bearing capacity.

Comments: Longitudinal and transversal unevenness and megatexture impact on vehicle wear due to the vibrations and roll movements they cause and the jerky driving that can be the result.

Background factors: Alignment can conceivably affect development of the road surface in a way that slightly reinforces the impact on vehicle wear.

2.5 Tyre wear

Significant impact: Macrotexture, microtexture

Moderate impact: Longitudinal unevenness, megatexture

Insignificant impact: Rut depth and shape, macrotexture, crossfall

No impact: Microtexture, friction, retroreflection, permeability to water, bearing capacity

Comments: Rut edges cause wear to tyres, the steeper the edges the greater the wear.

Longitudinal unevenness and megatexture increase heat on tyres and cause more wear.

Macro- and microtexture cause tyre wear.

Since there is a strong connection between micro-/macro-texture and friction there is also a connection with friction. Texture however has the major impact on tyres.

Background factors: Alignment, e.g. sharp bends, in combination with surface structure can also increase tyre wear.
2.6 Fuel consumption

Significant impact: Longitude

Moderate impact: Road surface stiffness

Insignificant impact: Rut depth and shape, microtexture, crossfall, permeability to water, bearing capacity

No impact: Retroreflection

Comments: Longitudinal unevenness and megatexture cause heat loss in shock absorbers and tyres

Macrotecture, and perhaps even microtexture, are significant for rolling resistance - the rougher the texture, the greater the rolling resistance. Rough macrotecture does not necessarily have a simply negative effect on rolling friction. If there is water on the road, less energy is used to remove it from the contact area between the tyres and the road the rougher the texture is. This in turn means reduced rolling resistance and reduced fuel consumption.

The stiffness of the road surface and its softening can be significant for rolling resistance and consequently for fuel consumption as well.

2.7 Travelling, route selection

Travelling and route selection refer here to journeys being brought forward or postponed, another route being chosen, or another mode of transport selected.

Significant impact: Longitudinal unevenness, megatexture, microtexture.

Moderate impact: Road surface stiffness.

Insignificant impact: Rut depth and shape, retroreflection, permeability to water.

No impact: Macrotecture, microtexture, crossfall.

Comments: Longitudinal unevenness and megatexture can involve a change of route or even a journey being cancelled. It can for example affect route selection for ambulances, the transport of fragile freight, etc.

Poor bearing capacity can mean that a road is closed for heavy traffic.
Friction is significant for travelling and route selection. Extremely low friction, macro- and microtexture, which is due to poor surfacing work, bleeding etc. can lead to roads being closed.

2.8 Freight damage
Significant impact: Longitudinal unevenness, megatexture.

Moderate impact: -

Insignificant impact: Rut depth and shape.

No impact: Macrotexture, microtexture, friction, retroreflection, crossfall.

Comments: Longitudinal unevenness and megatexture have an impact due to the roll movements that they cause. Also rut depth and shape can have certain significance in this respect.

2.9 Tyre-road noise
Significant impact: Megatexture, microtexture.

Moderate impact: Longitudinal unevenness.

Insignificant impact: Rut depth and shape, microtexture, permeability to water.

No impact: Retroreflection, crossfall, bearing capacity, friction.

Comments: Megatexture has a negative effect on tyre/road noise whilst macrotexture can have a negative as well as a positive effect depending on the wavelength.

The road surface’s porosity (permeability to water) is also of great significance.

Since texture is important for friction there should be a connection between the latter and tyre/road noise.

2.10 Pollution
Significant impact: Permeability to water.

Moderate impact: Rut depth.

Insignificant impact: Longitudinal unevenness, megatexture, microtexture, crossfall.
No impact: Rut shape, microtexture, friction, retroreflection, bearing capacity.

Comments: Permeability to water, and also to some extent macrotexture, are important for leading away water and consequently for water spray from tyres.

Background factors: Climate, in combination with the surfacing’s resistance to wear, should be of significance.

2.11 The life length of the road

Significant impact: Rut depth, longitudinal unevenness, bearing capacity.

Moderate impact: Megatexture, crossfall.

Insignificant impact: Permeability to water

No impact: Macrotexture, microtexture, retroreflection, friction

Comments: The impact of permeability depends on whether it is undesired or not.

Background factors: Alignment is of significance since wear to surfacing is greater in bends and uphill slopes.

Paved width and lane widths are of significance since they affect rut depth and shape.

2.12 Winter road maintenance

In VTI notat 21-93 no evaluation was made of the impact of the various road surface factors on winter road maintenance. Here is an evaluation of their direct impact on the road authority’s chances of meeting the requirements stipulated in the operational regulations and on the road authority’s costs for winter road maintenance. An evaluation is also made of the former’s impact on traffic, road-users and the surroundings. As far is known, there are no studies of these questions which means that there is a great degree of uncertainty in the evaluations.

Significant impact: -

Moderate impact: Rut depth, rut shape, longitudinal unevenness, megatexture, macrotexture, permeability to water.

Insignificant impact: -

No impact: Microtexture, retroreflection, crossfall, bearing capacity.
Comments:

Rut depth and shape and possibly megatexture can have an effect on snow clearance. Snow sometimes remains in surface unevenness (holes and ruts) and extra salt is then needed to remove it within the time limit stipulated by operational regulations. This applies to so called A-roads (salt roads).

Ruts and other unevenness across the road cause uneven wear to ploughshares and consequently shorten their service life. Even macrotexture affects wear.

Macro- and maybe microtexture too are important for friction even during the winter and should affect the measures required for maintaining satisfactory levels of friction in the event of rime frost, freezing rain and wet roads that freeze etc.

The effect of salt on draining surfacing (permeability to water) is less on non-porous surfacing. This is partly because the salt disappears down the pores and partly because it is quickly carried away with the melted snow.

Draining surfacing cools down quicker than one that is non-porous and this can mean that such surfacing has a tendency to become slippery.

3 Overview of evaluations

In VTI notat 21-93, there was a table summarising the work group’s assessment of the impact of various road surface factors on traffic, road-users and the surroundings (Schandersson et al., 1993). Below is a revised version of the table. Changes are indicated in bold type. The scale used is:

3 = significant impact
2 = moderate impact
1 = insignificant impact
0 = no impact

The scale is relative for each effect i.e. comparisons can only be made in columns and not in rows.
### Table 1: Summary of the impact evaluation of various road surface factors on a scale of 1-4.

<table>
<thead>
<tr>
<th>Trafficability</th>
<th>Road safety</th>
<th>Comfort</th>
<th>Vehicle wear</th>
<th>Tyre wear</th>
<th>Fuel consumption</th>
<th>Travelling, route selection</th>
<th>Freight damage</th>
<th>Tyre-road noise</th>
<th>Pollution</th>
<th>Life length of the road</th>
<th>Winter road maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rut depth</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Rut shape</td>
<td>2</td>
<td>?</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Unevenness, longitudinal Megatexture</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Macrotecture</td>
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<td>0</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Microtexture</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Friction</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Retroreflection</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Crossfall</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Permeability to water Bearing capacity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Road surface stiffness</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
4 Further overview matrices
4.1 Material and structural properties versus functional properties

In the revised matrix above, an evaluation is made of the impact of the various road surface factors on road-users and the surroundings. In this chapter an attempt is made in two stages via the road’s so-called functional properties, to assess the impact of different material and structural properties on road-users and the surroundings.

Material and structural properties:
- Microtexture (quality of stone material, bleeding)
- Macrotexture (type of surfacing, stone size, bleeding)
- Megatexture (cracks, pot holes, stripping)
- Unevenness (settlement, uneven frost heave, thawing blocks)
- Crossfall
- Rut depth and shape
- Edge drop
- Permeability to water
- Stiffness
- Colour

Primary functional properties:
- Friction properties (braking and lateral force impact)
- Rolling resistance properties
- Tyre wear properties
- Visibility, light reflection
- Noise and sound information properties
- Vibration properties
- Rolling movements
- Drainage capacity

Secondary (derived) functional properties
- Water depth (puddle formation)
- Ice on the road (as effect of difficult winter road maintenance)
- Snow on the road (as the result of difficult winter road maintenance)
Table 2 Evaluation of the significance of various material and structural properties for the functional properties of road surfaces (+ certain significance, ++ great significance).

<table>
<thead>
<tr>
<th>Material and structural properties</th>
<th>Primary functional properties</th>
<th>Secondary functional properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Friction</td>
<td></td>
</tr>
<tr>
<td>Microtexture</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rolling resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tyre wear</td>
<td></td>
</tr>
<tr>
<td>Material and structural properties</td>
<td>Noise and sound information</td>
<td></td>
</tr>
<tr>
<td>Megatexture</td>
<td>Vibration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roll movements</td>
<td></td>
</tr>
<tr>
<td>Unevenness</td>
<td>Surface drainage</td>
<td></td>
</tr>
<tr>
<td>Crossfall</td>
<td>Visibility</td>
<td></td>
</tr>
<tr>
<td>Edge drop</td>
<td>Water depth</td>
<td></td>
</tr>
<tr>
<td>Alignment</td>
<td>Ice on the road</td>
<td></td>
</tr>
<tr>
<td>Rut depth</td>
<td>Snow on the road</td>
<td></td>
</tr>
<tr>
<td>Permeability to water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2 Functional properties versus traffic effects

The traffic effects included in the matrix below are vehicle operating costs divided into fuel consumption, tyre wear and repair costs, travelling time including vehicle speed and trafficability/accessibility, traffic safety, comfort and finally environmental impact. A + indicates that there is a connection.

**Table 3** Evaluation of the functional properties of a road surface that have significance for various traffic effects.

<table>
<thead>
<tr>
<th></th>
<th>Fuel consumption</th>
<th>Tyre wear</th>
<th>Repairs</th>
<th>Travelling time</th>
<th>Traffic safety</th>
<th>Comfort</th>
<th>Environment (exhaust fumes, noise, salt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tyre wear properties</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Noise and sound data.</td>
<td></td>
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<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrations</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roll movements</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface draining</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visibility, light reflection</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Water depth</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Ice on the road</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Snow on the road</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Comments on the evaluations

Fuel consumption  *Rolling resistance* has great significance for fuel consumption. The presence of *water* or *snow* on the road increases rolling resistance and consequently fuel consumption too. Crossfall and alignment also affect fuel consumption.

Tyre wear  Even crossfall and alignment, which are not included in the tyre wear properties of the surfacing, have significance for tyre wear.

Repair costs  Vibrations and roll movements cause increased stress and wear to different vehicle components such as springs and shock absorbers.
Travelling time

Friction on the road has a major impact on trafficability.

The noise level inside the vehicle can have a certain impact on speed due to the discomfort it can cause in the driver.

Vibrations and roll movements affect the driver’s ability to handle the vehicle. The risk of damage to the vehicle, the freight etc. can also cause the driver to reduce speed.

Visibility and light reflection are important when it is raining and dark.

Water on the road increases the risk of aquaplaning, whilst ice and snow increase the risk of accidents occurring as a result of skidding. Both water and snow therefore can be expected to have a restraining effect on speed.

Road safety

Friction is of key significance for traffic safety.

Vibrations and roll movements affect the ability of the driver to handle the vehicle safely.

Visibility and light reflection are important especially when it is raining and dark.

Water on the road increases the risk of aquaplaning whilst snow and ice increase the risk of accidents occurring due to skidding.

Comfort

The majority of the functional properties indicated such as friction, visibility, water or ice or snow on the road surface, are significant in terms of the accident risk experienced and consequently for the level of comfort experienced too.

Both noise, vibrations and roll movements have a direct impact on the degree of travel comfort both as concerns feelings of discomfort and impact on health.

Environment

Rolling resistance is significant for fuel consumption and consequently for exhaust emissions.

Tyre wear properties impact on the amount of tyre debris that ends up on the road and in the vicinity of the road.

Noise and vibrations disturb those living in the vicinity of the road. Vibrations can also cause damage to buildings and other constructions.
Snow and ice on the road can also lead to increased use of salt.

As a supplement to the above comments, a memorandum by Georg Magnusson of the Swedish National Road and Transport Research Institute is attached to Appendix 1. This deals with the functional properties of roads, in particular road surface unevenness, and their significance for road users, road authorities and the surroundings. As far as traffic safety is concerned, there is a discussion as to how road surface unevenness affects the driving dynamics of vehicles and driver performance.
5. References


FUNCTIONAL CHARACTERISTICS OF ROADS

Definition

The functional characteristics of roads can be defined as road surface properties that in some way or other influence the road users, the road authorities and/or the environment around the road. Examples of such functional characteristics are the road user’s demand for traffic safety and low vehicle running costs, the road authorities’ demand for limited road wear and damage and the demands from people living near the road for low noise level and demands, maybe primarily from unprotected road users, for road surfaces reducing splash and spray from passing vehicles.

Road user effects

Traffic safety

Vehicle handling

The vertical swinging motion of the road wheels of a vehicle running on an uneven road surface will result in varying dynamic wheel loads and thus varying ground contact forces in all directions parallel to the road surface. These ground contact forces are used for controlling the vehicle, i.e. steering, braking and accelerating. Varying ground contact forces result in reduced effects of the controlling measures executed by the driver and also in reduced predictability regarding the effects of these measures, in extreme cases leading to a traffic accident.

The side force characteristics of the tyre are very important for the vehicle’s behaviour in curves. Figure 1 gives an example of the typical relationship between wheel load, side force and slip angle.
When the vehicle driver wants to change the direction of travel, e.g. to enter a road curve, the measure to be taken is to turn the steering wheel so that the front road wheels will be given a slip angle. The slip angles of the front wheels produce side forces of which the magnitude depends on the tyre type, the steering angle and the wheel load. The thus created side forces affect the vehicle and turn it in the direction of the force. At the same time side forces at the rear wheels will be created opposing the yaw movement of the vehicle. The sum of these forces counteracts the centrifugal force acting on the vehicle. As long as the wheel loads are lower than the load corresponding to the upper side force limit, which is normally the case, an increase in wheel load will give an increase in attainable side force at a given slip angle. Due to the upwards convex shape of the relationship, the increase of the side force for a given increase in wheel load at a given slip angle will be less than the decrease in side force caused by an equally large decrease of the wheel load. Consequently, an uneven road will always mean a reduction of the vehicle’s cornering ability compared to a smooth road.

In the case of braking and accelerating the possibility to use the friction forces between tyre and road surface again depends on the extent to which the tyre/road contact forces can be maintained. The factors decisive for the magnitude of the friction forces are the wheel load and the relative velocity of the sliding motion of the road contact area of the tyre relative to the road surface (Figure 2).
"Slip" is defined (see formula below) as the difference between the rotational velocity of the wheel in a free rolling state and the real rotational speed while braking divided by free rolling rotational speed. The slip value is normally expressed as a percentage. "Spin" is the corresponding quantity defined for driving conditions.

\[ s = \frac{\omega_f - \omega_s}{\omega_f} \]

When a vehicle wheel is braked it will be affected, apart from the wheel load, by two counteracting torques. One braking torque originating from the wheel brake and one driving torque of which the magnitude depends on friction force between the tyre and the road multiplied by the axle height, i.e. the distance between the road surface and the axle centre. During braking, the braking torque is regulated to give the requested retardation of the vehicle. If the wheel load, e.g. due to the road unevenness, is reduced the friction force will also be reduced and, consequently, also the driving torque acting on the wheel, meaning that the slip value will increase. If the slip value exceeds the value corresponding to maximum friction number (see Figure 2) the wheel will lock almost instantaneously. Locked rear wheels will give the vehicle a tendency to rotate 180° with respect to the vertical axis through the centre of gravity and than continue the travel backwards. Locked front wheel means that the steering ability will be lost but the vehicle is anyway stable. With all wheel locked the behaviour of the vehicle is unpredictable but the braking distance will normally be longer than if the braking was carried out with all wheels braked but not locked. Braking of a road vehicle should thus always be carried out in such a way that the locking of one or more wheels is avoided. An uneven road surface may in some cases increase the risk for locking the wheels, especially in road curves. It should, however, be noted that this problem would decrease as the use of ABS systems increase.

Figure 2. The basic shape of the relationship between friction number, slip and spin.
Driver performance

The uneven road’s primary influence on the vehicle is to put the road wheels in a mainly vertical swinging motion, of which the amplitude depends on the degree of unevenness and the vehicle’s speed. Via the tyres, the springs, the shock absorbers, the body and the seats of the vehicle this swinging motion will be transferred to the driver and to the passengers.

The influence of vibration on man depends on the frequency content, amplitude, direction and duration of the vibration. The frequency content is primarily dependent on two dominating resonance frequencies in the vehicle, one associated with the swinging motion of the vehicle’s body on the suspension and the other emanating from the wheel axle swing motion between the vehicle suspension and the springing action of the tyre. The resonance frequency of a passenger car body is in the range of 0,8 Hz to slightly over 1 Hz. For a heavy vehicle with air springs the resonance frequency of the body motion (bounce) is in the range of 1 Hz to 1,5 Hz while for a steel sprung heavy vehicle the resonance frequency is around 3 - 4 Hz. The resonance frequency for the axle motions, the so-called wheel hop frequency, is around 10 Hz for passenger cars and up to 15 Hz for heavy vehicles.

According to the revised International Standard ISO 2631-1 "Mechanical vibration and shock – Evaluation of human response to whole-body vibration – Part 1: General requirements" (second edition 1997-05-01) man is most sensitive for vertical whole-body vibrations in the range of 4 – 10 Hz while for horizontal vibration the highest sensitivity is in the frequency range of 0,6 to 1,6 Hz. The resonance frequency of body bounce is thus mainly outside of the frequency ranges for maximum human sensitivity. Only the body bounce for steel sprung heavy vehicles is close to these ranges.

Horizontal vibrations are more disturbing than vertical vibrations of the same amplitude. High amplitude transversal accelerations may be the result if the road profiles in the left and right wheel tracks are out of face and also have a wavelength exciting the rolling motion of the vehicle. Little information is available regarding the resonance frequency for the rolling motion but 1 Hz is a likely figure for passenger cars and thus just in the middle of the frequency range most disturbing for man. For heavy vehicles this resonance frequency is supposed to be somewhat lower and depending on height of the load, but at least in one case the resonance frequency of about 1Hz has been observed. The important wavelengths in this respect should be those longer than 20 m.

The revised version of ISO 2631 covers the influence of whole-body vibration on health, comfort, perception and motion sickness. The original version of ISO 2631 "Guide for the evaluation of human response to whole-body vibration” also contained information on exposure limits regarding performance. It has, however, later been recognised that no firm evidence for such guidance exists and thus the present version of ISO 2631 does not give any guidance in these respects. However, even if there is no guidance as to the evaluation or establishment of limits with respect to performance, it nevertheless seems likely that those frequency ranges affecting health and comfort also would have an influence on performance.

The road unevenness can also induce high levels of infrasound in road vehicles, especially in modern buses with bodies mainly consisting of large flat areas of glass and sheet metal. It had been shown at VTI that infrasound could create fatigue and,
consequently, reduced performance. Infrasound is considered to contain up to and including 20 Hz with a suggested lower limit of about 2 Hz. The wheel hop frequency of buses would thus be able to force poorly damped bus body panels to vibrate in the infrasound frequency range.

Trafficability (Level of service)

The road nets of developed countries are mainly in such a state that trafficability is secured. If trafficability is regarded as a continuous variable it is possible to define different levels of trafficability which can be expressed as length of the travel time.

An uneven road can be expected to cause reduced speed and thus longer travel time between to points, either because the driver or a passenger feel ill at ease due to vibrations in the vehicle, or because the driver thinks that the vehicle will be damaged at a higher speed. If there is an alternative smoother road leading to the intended destination, a certain driver may chose that road even if it is somewhat longer. Studies of such choices between short uneven roads and smoother but longer roads have been carried out, but no conclusive results have been reported. The reason for this lack of result is probably that the preference for a certain road alternative does not depend only on the relationship between unevenness and distance. It also depend on the driver’s tolerance to vibration, his expectations about how the different available road alternatives affect the running costs of the vehicle expressed in vehicle and tyre wear and fuel consumption, the beauty of the surroundings, differences in driving experience, available travel time etc.

Riding Comfort

What is said above about driver performance is also applicable to riding comfort. The previous version of ISO 2631 described a time dependent comfort evaluating method. However, according to the present version of the standard, "there is no conclusive evidence to support a universal time dependency of vibration effects on comfort". The evaluation of riding comfort is based on a frequency weighted RMS-value. The values in the following table give approximate indications of likely reactions to various magnitudes of overall vibration values in public transport. It should be noted that this table is given in an informative Annex to the standard.

<table>
<thead>
<tr>
<th>RMS acceleration $\frac{m}{s^2}$</th>
<th>Comfort level</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.315</td>
<td>not uncomfortable</td>
</tr>
<tr>
<td>0.315 – 0.63</td>
<td>a little uncomfortable</td>
</tr>
<tr>
<td>0.5 – 1.0</td>
<td>fairly uncomfortable</td>
</tr>
<tr>
<td>0.8 – 1.6</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>1.25 – 2.5</td>
<td>very uncomfortable</td>
</tr>
<tr>
<td>&gt; 2.0</td>
<td>extremely uncomfortable</td>
</tr>
</tbody>
</table>

It is, however, pointed out in the Annex that "the reactions at various magnitudes depend on passenger expectations with regard to trip duration and the type of activities passengers expect to accomplish (e.g. reading, eating, writing, etc.) and many other factors (acoustic noise, temperature etc.).
Vehicle running costs

Vehicle wear
The static and dynamic vertical and horizontal forces acting in the contact area between tyre and road having a decisive influence on the manoeuvrability of the vehicle as well as affecting driver and passengers also create forces in the vehicle. These forces result in stress and strain in different parts of the vehicle, as well as in relative motions between different parts in e.g. the suspension system. These motions will give wear and, consequently, loss of construction material which in the event will result in co-operating components falling apart, which might be the case for a ball joint, or to a fracture due to overstress of the material. A fracture without preceding wear may of course happen due to overload or a faulty dimension. In most cases, however, the reason would be metal fatigue.

Tyre wear
The tyre wear depends on a number of factors among which the driving behaviour probably is the dominating one. Other factors are tyre design, road and air temperature and the characteristics of the road in terms of texture and unevenness, i.e. the road profile. The effect of the texture can be regarded as a purely material abrasive process, which probably is responsible for the main part of the tyre wear. The influence on the tyre wear from the longer wavelengths, in the unevenness range, is related to the heating of tyre when it works as a suspension element between the road surface and the wheel axle. Increased temperature in the tyre carcass and the tread rubber will result in increased wear, all other factors kept constant.

Fuel consumption
The driving behaviour is the decisive factor even for fuel consumption but the road surface characteristics also have some effect. Two factors can immediately be recognised; tyre rolling resistance and loss of energy in the shock absorbers.

The rolling resistance depends maybe mainly on the texture but the longer wavelengths also will cause increased rolling resistance that must be overcome sacrificing energy, i.e. increased fuel consumption. The heating of the tyre, due to the flexing action on uneven roads, will normally also result in increased fuel consumption.

The vertical swinging motion of the vehicle body activated by an uneven road surface is damped by the shock absorbers by means of transforming kinetic energy into heat. The chemical energy of the fuel is the only energy that is brought to the system. An uneven road causing large vertical swinging motions will thus request a higher energy contribution than a smoother road if the speed is kept constant.

Influences on road authorities
As previously said, the uneven road will put the vehicle in a vertical swinging mode. The associated vertical accelerations will together with heavy masses, i.e. for heavy goods vehicles, cause large variations in dynamic wheel loads. These variations depend on the wavelength and amplitude content of the longitudinal road profile, the speed and the mass and suspension characteristics of the vehicle.
The magnitude of the dynamic wheel load variations is often given as the "Dynamic Load Coefficient" (DLC) defined as:

\[ DLC = \frac{RMS \text{ dynamic wheel load}}{\text{static wheel load}} \]

Normal range of DLC is 0.1 to 0.3 while DLC = 0.4 may be a typical value for bad tandem axle configuration. The maximum value of the dynamic wheel load may often be equal to three times the RMS value. An axle having a DLC of 0.2 may thus give temporary axle loads (sum of static and dynamic axle load) of 160% of static axle load. According to the OECD report "Dynamic loading of pavements", most of the load maxima probably is about 120% of static load and every twenty load maximum reaching 140%.

The so-called "fourth-power law" says that the road wear is proportional to the fourth power of the wheel load. This means that the loss in length of life of the road at wheel loads exceeding static load with a certain amount, is much higher than the gain in length of life when the wheel loads are below the static load with the same amount. Consequently the road wear will increase with increasing dynamic wheel load variations although the average value of the wheel load over a sufficiently long section of the road is equal to the static wheel load. For example, according to the "fourth power law" a wheel load of 120% of static load is about twice as aggressive to the road as the purely static load would be.

The magnitude of the power of "fourth-power law" has in the last few years been questioned and it is believed to vary at least in the range of 3 – 6, depending on road design. However, there seems to be a general agreement about the idea of an exponential relationship. It should be noted that only the wheel loads from heavy vehicles is expected to have any influence on the length of life of the road.

The large wheel load variations are related to the body bounce frequency with superimposed smaller load variations related to the wheel hop frequency. A local bump of the road will put a passing vehicle in a swinging mode at the body bounce frequency. If all heavy vehicle are supposed to have the same body bounce frequency and pass the bump at the same speed, the pattern of wheel load variation along the road will be the same for all passing heavy vehicles. This phenomenon is called ”spatial repeatability” and indicates that high wheel loads on the road will occur at the same spots along the road, thus leading to premature damage on those spots. Before the introduction of air springs on heavy vehicles the body bounce frequency of around 3 - 4 Hz was almost universal for heavy vehicles and due to speed limits the speed on a certain road was also about the same for all heavy vehicles. At 70 km/h this means that the distance between individual high load spots are about 6 m. In the present situation, with a mixture of steel sprung and air sprung heavy vehicles, the "spatial repeatability” should be of less importance. In the near future, however, when virtually all steel sprung heavy vehicles probably have been replaced by air sprung vehicles the problem would increase although the distance between high load spots would be about 15 m.
Effects on the surroundings of the road

A vehicle travelling along a road incurs a varying load on the road surface. This will result in vibration waves being transmitted in all directions in the road surface, as well as down through the road structure. These vibrations may, depending on intensity and frequency, be disturbing for people living close to the road and/or damage nearby buildings. The intensity and frequency depends on the speed and the characteristics of the passing vehicles and on the wavelength and amplitude of the longitudinal road profile.

The uneven road will also have an influence on noise generated by the traffic; maybe mainly rattling noise generated by the vehicle itself or its load. Vehicle generated soil vibrations may also cause disturbing noises. Possibly with exception of the rattling the culprit, even in this case, should be the heavy vehicle.