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Environmental Impacts and Fuel Efficiency of Road Pavements

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Environmental Impacts and Fuel Efficiency of Road Pavements

Summary

In many countries, environmental issues and energy consumption play an increasingly important role in the planning process for highway projects. Literature data on fuel efficiency and greenhouse gas emissions related to construction and use of the road are compiled in this report.

Studies in Sweden and Canada reveal that energy consumption during construction, maintenance and operation of roads is lower for asphalt pavements than for concrete pavements. Green House Gas emission (GHG) and Global Warming Potential (GWP) are therefore always lower for asphalt.

However the bulk of energy is consumed by traffic using the road and only 2 to 5% of the total consumption is required for construction, maintenance and operation of the road. Fuel consumption on different road surfaces is therefore the logical subject of several studies. Of particular interest are road related factors such as surface characteristics (texture), bearing capacity and viscoelastic behaviour.

All studies confirm that surface texture is a predominant factor. However, the outcome of various studies is sometimes conflicting regarding differences in fuel efficiency on asphalt and concrete roads. It is fair to say that the differences between pavement types as such - asphalt or concrete - are not significant. The condition of the pavement (good surface characteristics) is more important in this respect for both asphalt and concrete roads. Optimal maintenance of roads is therefore a tool to reduce fuel consumption and green house gas emission.

Besides energy consumption decision makers need also to consider several other factors in order to satisfy the multiple requirements of protecting the environment (limiting green house gas emission), saving energy, reducing traffic noise and ensuring good driving safety and comfort.

Introduction

Environmental questions have become an important part of the decision-making processes for highway projects in many countries. Advantages of different road pavements from environmental viewpoint and energy consumption are therefore an important part of the planning processes. Fuel efficiency and greenhouse gas emission of different road pavements has been the object of research projects and studies all over the world.

In this report, some knowledge in the area has been compiled. The document starts with an overview about energy consumption and other environmental impacts during road construction, maintenance and operation. After that the focus of the document is on effects of the traffic using the road and the fuel consumption for different types of vehicles and pavements.

1. Fuel economy of road pavements at different stages

A method to obtain a good overview of the environmental impact of highways at construction, maintenance and operation is to perform a LCA, Life Cycle Assessment.

IVL, the independent Swedish Environmental Research Institute, has carried out a LCA study of roads in collaboration with NSRA, the National Swedish Road Administration. A report in English from the study was published in 2001 [2]. NSRA provided data for the study while IVL made all calculations. The methodology used in the study followed the recommendations from SETAC, Society of Environmental Toxicology and Chemistry.

1.1. Total energy consumption at construction, maintenance and operation

The main results from the IVL-study are shown in figure 1 to 4 (from the IVL report [2]). The total energy consumption divided into construction, maintenance and operation (i.e. mainly traffic lights and lighting) during 40 years of a 1 km long and 13 m wide road is shown in figure 1. Production of road materials such as bitumen and cement are included in the study. The total energy consumption was calculated as 23 TJ for the asphalt road and 27 TJ for the concrete road. Of the total energy consumption, the 40 years of operation accounts for a large part. This energy consumption originates from consumption of electrical energy from road lighting and traffic control (approximately 12 TJ) i.e. nearly all of the energy consumption for the operation of the road. The calculations have been divided into use of conventional diesel engines and low emission diesel engines in the vehicles used in the construction and maintenance of the road. Different calculations have also been made for use of hot or cold asphalt mixes.

1.2. Inherent or feedstock heating value

In life cycle analysis the question always arises whether if the "inherent" energy in the bitumen should be taken into account when comparing cement and asphalt pavements. The inherent energy bound in the bitumen in the asphalt layer is also shown in figure 1. Bitumen is a hydrocarbon by origin. Potentially these hydrocarbon molecules could be transformed into fuels like gasoline and diesel when processed in a refinery-cracking unit ("the inherent energy"). But there are many reasons for not taking the energy value inherent in the bitumen into account:

- Bitumen in the asphalt pavement is not burned at the end of the life cycle and no CO_2 emission takes place.
- Bitumen can even be re-used at the highest possible performance level; it is laid down as new asphalt pavement, and can be recycled several times.
- In many countries hot mix contains 30 to 50% of reclaimed asphalt granulate. Some asphalt plants exist which can recycle up to 90% recovered asphalt granulate.
- The recycling of asphalt means automatically that the aggregates are also re-used at the highest possible performance level.
- Cement bounded materials can normally only be re-used at a much lower performance level, such as in foundations.

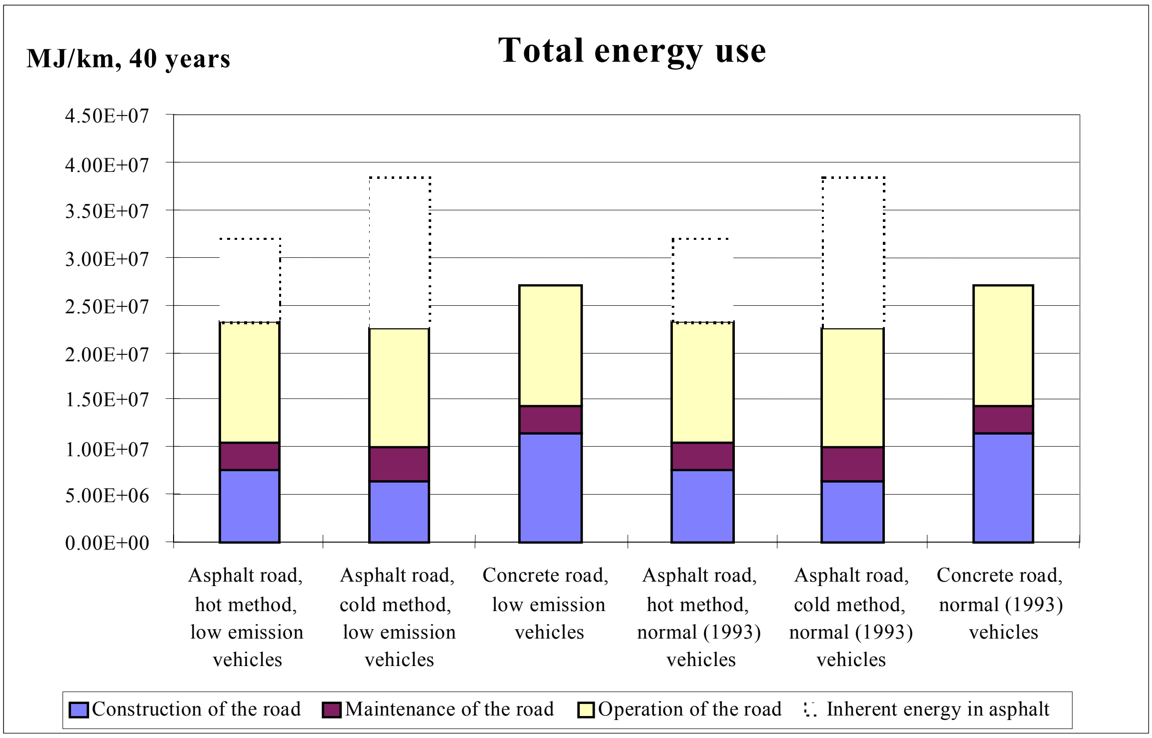

Figure 1 - Total energy consumed over a 40 years period
For a 1 km long and 13 m wide road during construction and 40 years of maintenance and operation (lighting, traffic lights, winter treatment) [2] IVL

1.3. Greenhouse gas emission

The emissions of greenhouse gas, i.e. CO_2, SO_2 and NO_x for a 1 km long and 13 m wide road is shown in figure 2 to 4. The dominating activity for the emission of SO_2 and CO_2 is in the initial construction of the road. The maintenance of the road is the second largest source of the emissions and for NO_x emission this activity gives a significant contribution. The operation of the road (i.e. mainly traffic lights and lighting) accounts only for a small part of the total emissions. In total, the concrete road gives much larger emissions of greenhouse gases per km in the construction phase, compared with the asphalt road.

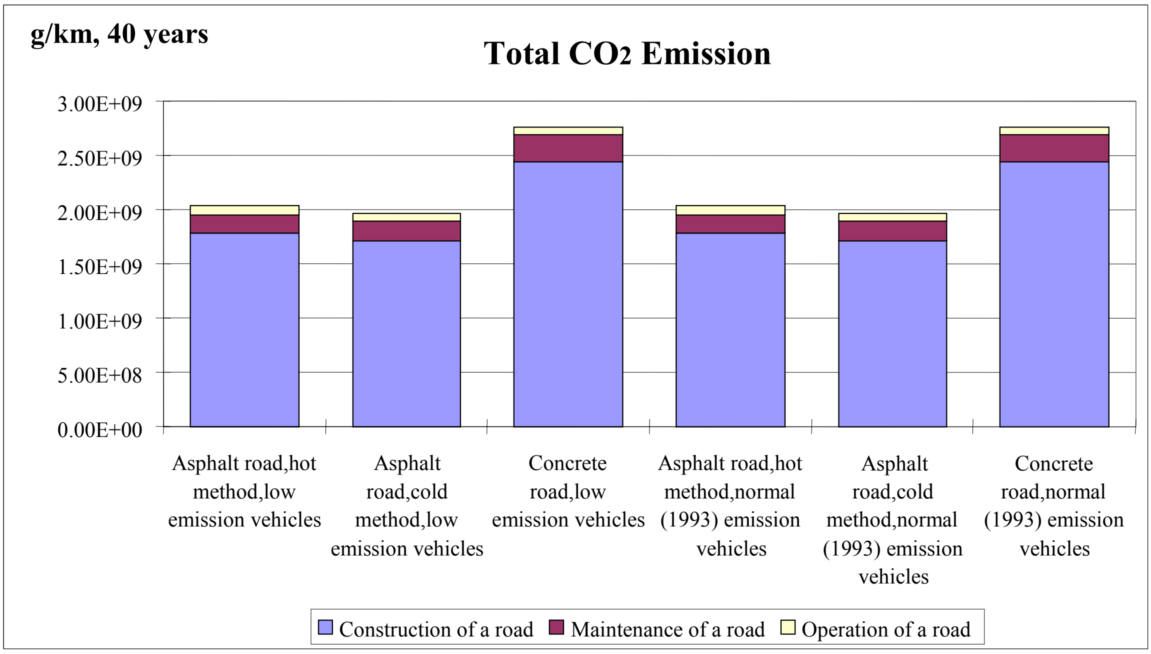

Figure 2 - Total CO_2 emission over a 40 years period
For a 1 km long and 13 m wide road during construction and 40 years of maintenance and operation (lighting, traffic lights, winter treatment) [2] IVL

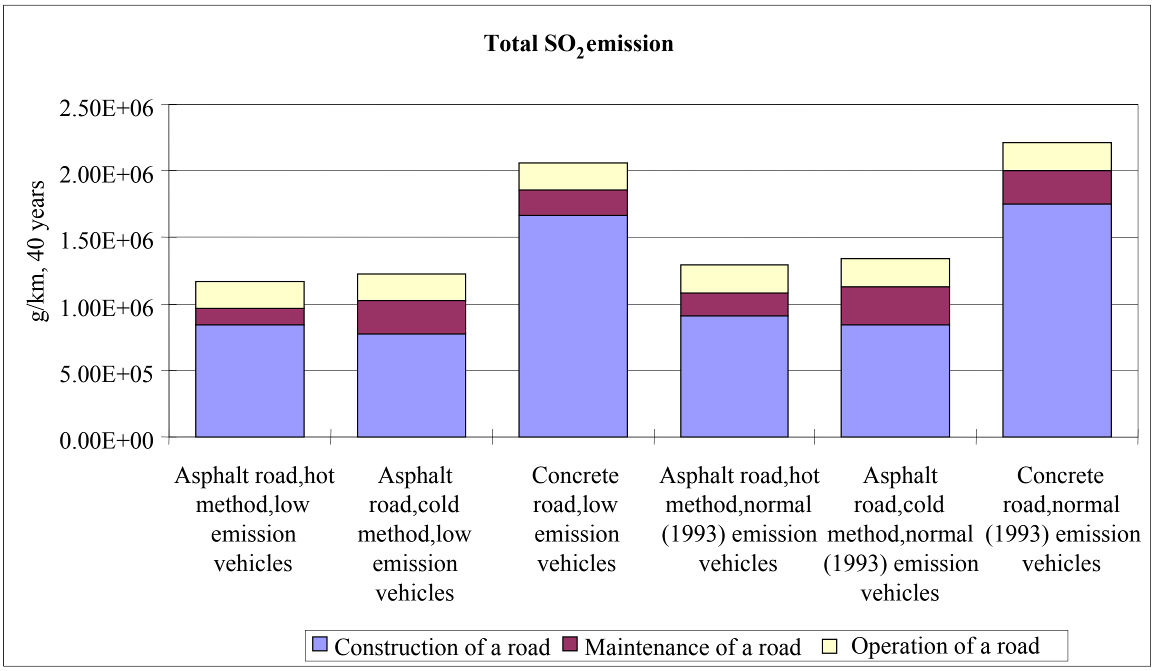

Figure 3 - Total SO_2 emission over a 40 years period
For a 1 km long and 13 m wide road during construction and 40 years of maintenance and operation (lighting, traffic lights, winter treatment) [2] IVL

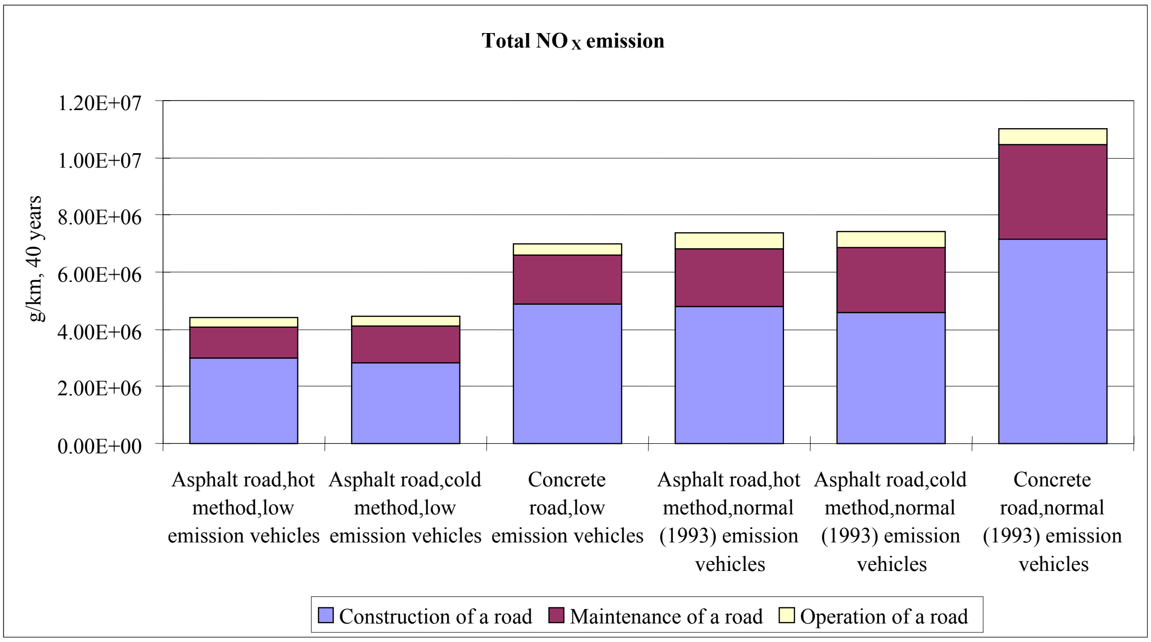

Figure 4 - Total NO_x emission over a 40 years period
For a 1 km long and 13 m wide road during construction and 40 years of maintenance and operation (lighting, traffic lights, winter treatment) [2] IVL

1.4. Energy consumption of traffic

An approximation of the energy consumption of the traffic during the 40 years of operation gives a total of 229.2 TJ based on traffic intensity of 5000 cars/day and with a fuel consumption of 0.1 litre fuel/km per car, including production of the fuel. Calculations of the energy use of the road compared with the energy use of the traffic are presented in Table 1 for a traffic intensity of 5000 cars/day, with and without electric energy consumption for road lights and traffic control. In this case, the road traffic during 40 years accounts for ten to twenty times larger energy consumption than the construction, maintenance and operation of the road. Differences in the energy needed for the construction phase play therefore a minor role [2] IVL.

The use of energy for 'construction, maintenance and operating' of the road over a period of 40 years as a percentage of the energy use of the traffic during this period (with a traffic intensity of 5000 vehicles/day)		
Road type	**With road illumination and traffic control**	**Without road illumination and traffic control**
Asphalt road, hot method	10.1%	4.9%
Asphalt road, cold method	9.9%	4.7%
Concrete road	11.8%	6.6%

Table 1 - The energy needed for "construction, maintenance and operating" a road as a percentage of the energy use of the traffic [2] IVL

At higher traffic volumes the road traffic contributes an even higher proportion of the total energy consumption. Armines, Centre d'Energétique de l'Ecole des Mines de Paris, France, has made a study on Life Cycle Assessment of 1 km of road 2x2 lanes [3]. The result of the study shows (see figure 5) that energy consumption of the traffic during 30 years gives a total energy consumption of 1430 TJ based on French traffic class TC6 (equivalent to a total traffic of 25 million heavy vehicles and 100 million private cars during 30 years). The energy consumption during construction, maintenance and end of life was 23 TJ. This means construction and maintenance phases represent only about 2% of the total energy consumption during the whole life cycle of the road.

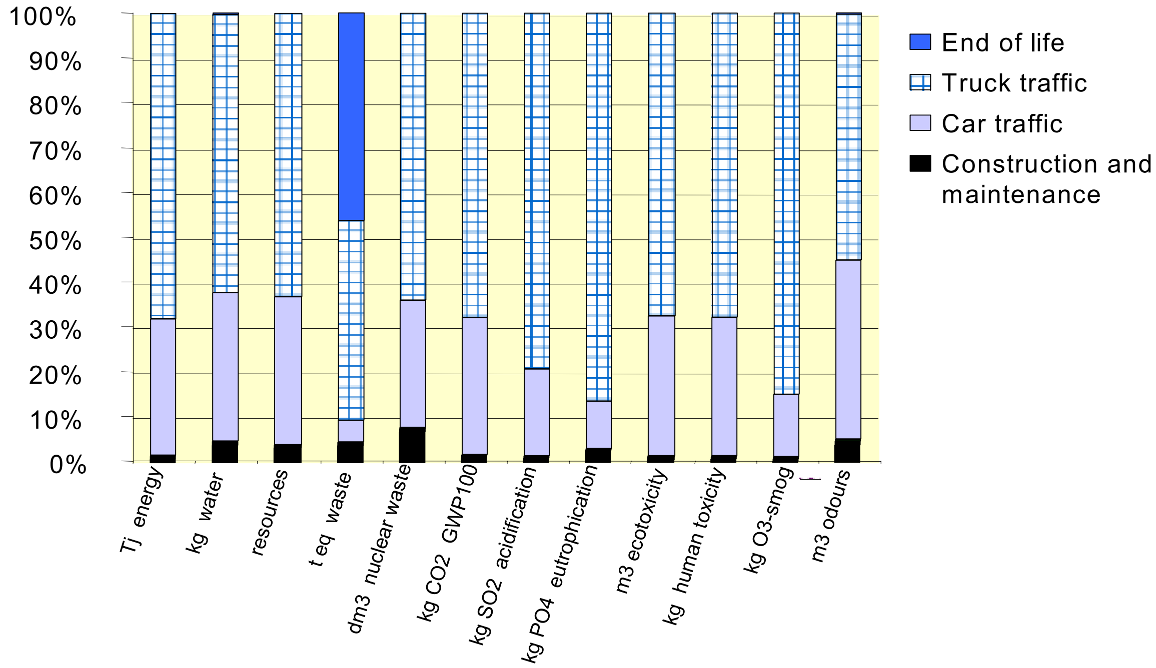

Figure 5 - Ecoprofile of different stages of a road

Confirmation can be found in a report published by Colas in 2003 on the environmental road of the future [16]. It is observed that, over a period of 30 years, traffic consumes between 10 and 345 times more than road construction and maintenance, depending on whether the traffic is light or heavy, as shown in figure 5bis.

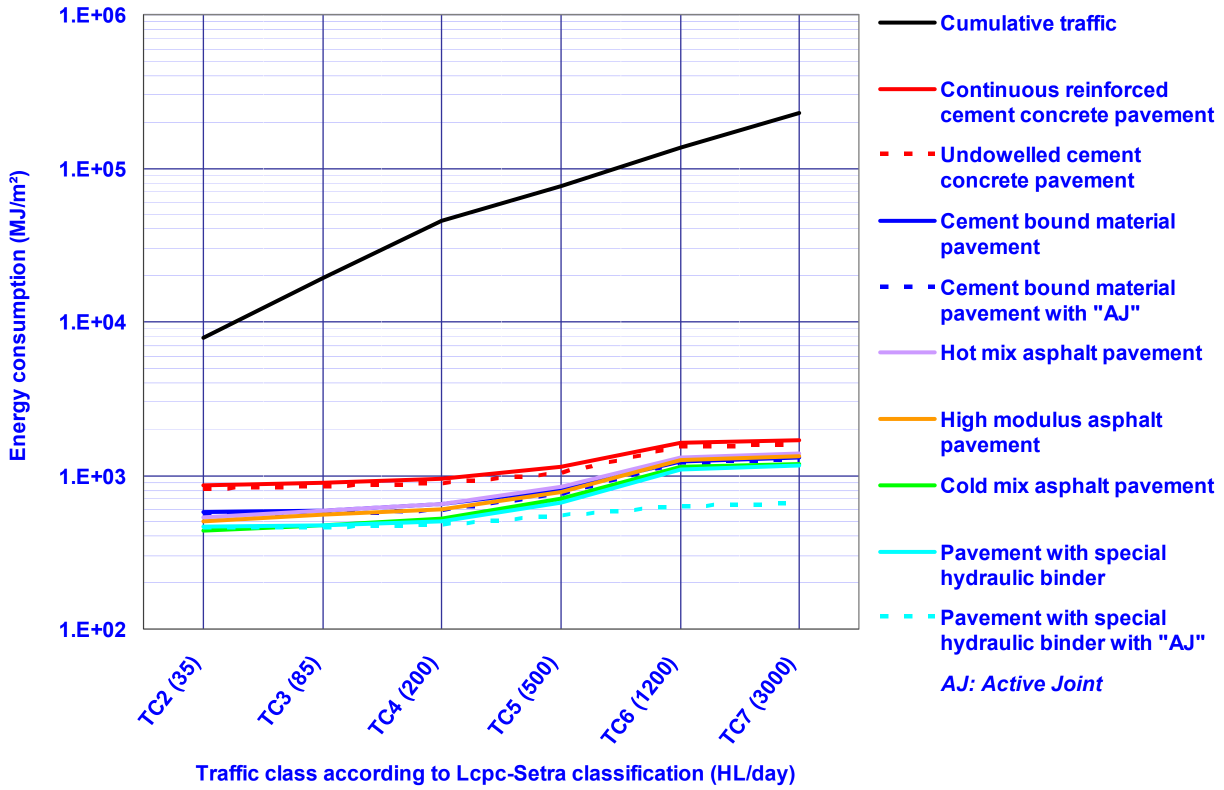

Figure 5bis - Energy consumption for different types of pavement structure *(construction + maintenance of the pavement and safety barriers), compared with the consumption of total cumulative traffic [16]*

Traffic classes and cumulated traffic over 30 years are indicated below:

Traffic class	TC2	TC3	TC4	TC5	TC6	TC7
Daily heavy lorries traffic (per direction)	35	85	200	500	1200	3000
Daily vehicles traffic (per direction)	538	1 308	3 077	7 692	18 462	46 154
Cumulated vehicles traffic (in million for the both directions)	20	50	116	290	700	1740

1.5. Study in Canada about energy requirements and greenhouse gas emission

The Athena Sustainable Materials Institute in Canada [4] has also performed a study on behalf of the Canadian Cement Industry about energy requirements and GHG (greenhouse gas) emissions for concrete and asphalt pavements. In these calculations only the construction and maintenance of the road is taken into account and recycling effects were not taken into account. Some of the results from the study are presented in figure 6 and 7 below.

In the Athena study, the high-traffic pavements that are compared are not equivalent from a design perspective. If the input data used in this study are used in the AASHTO design model they give a desired thickness for the cement pavement of approximately 50 mm extra. The cement concrete pavement is clearly underdesigned and the asphalt pavement somewhat overdesigned. The conclusion of this is that the presented energy requirements and GHG emissions for high traffic pavements are too low for concrete and too high for asphalt pavements.

In figure 7 the result of the Athena study is presented as far as the GWP (Global Warming Potential) is concerned. Even for the non-equivalent structure used for the study the GWP of the cement pavement is significantly higher. When the thickness of layers is corrected the asphalt performs even better; therefore asphalt always has the lowest Green House Gas emission (GHG) and the lowest Global Warming Potential (GWP).

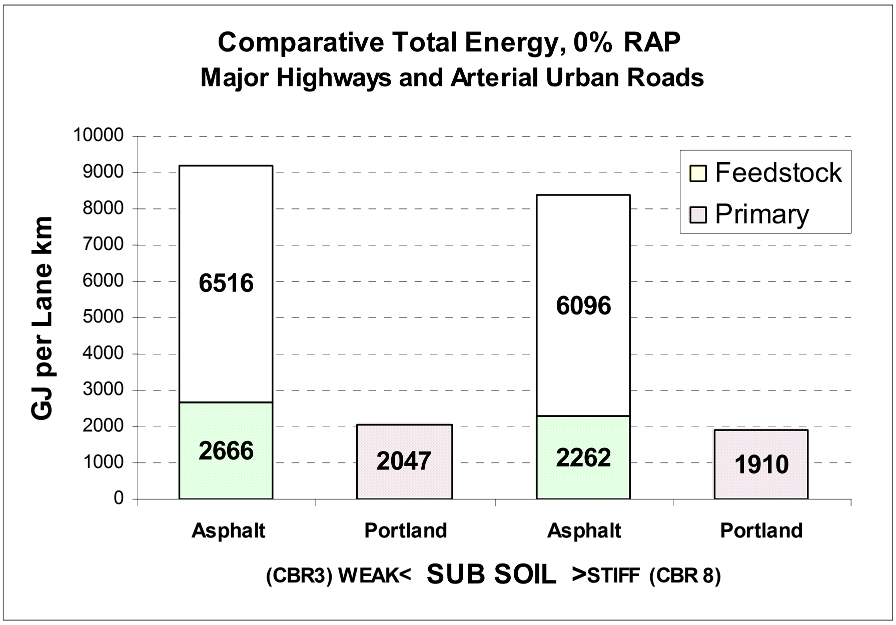

Figure 6 - Athena study – Comparative Total Energy
Not corrected for the thickness deviations as mentioned in the above comment and no recycling. Correction means that asphalt will be better in all situations; certainly when repeated recycling is taken into account

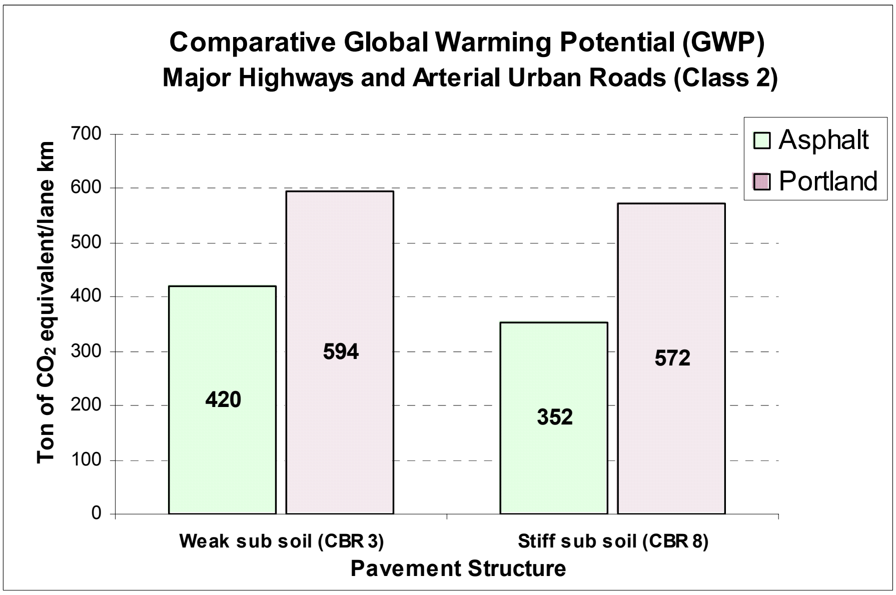

Figure 7 - Athena study – Comparative Global Warming Potential
Not corrected for the thickness deviations as mentioned in the above comment and no recycling. Asphalt shows by far the lowest Global Warming Potential

1.6. Conclusion 1

The total energy consumption during construction, maintenance and operation of roads is lower for asphalt pavements than for concrete pavements. Also the greenhouse gas emissions during construction, maintenance and operation are lower for asphalt pavements.

However the energy consumption of the traffic itself on a road is during its lifetime of overwhelming importance (95 to 98%). Depending on the traffic volume the energy use for construction, maintenance and operating the road is less than 2 to 5% of the energy used by the traffic itself. Therefore it is legitimate to focus on how different road pavement surfaces effect the fuel consumption of vehicles driving on it.

2. Factors impacting energy/fuel consumption for a vehicle

There are many factors that impact the energy/fuel consumption for a vehicle. These factors can be divided into following parts:

- Thermodynamic efficiency of the engine to transfer heat into mechanical power
- Rolling resistance: due to tyre/pavement effect for each wheel
- Air resistance: effect of speed and aerodynamic shape
- Gradient resistance: effect of road slope and vehicle mass
- Inertia resistance: effect of vehicle mass and acceleration
- Driveline losses in the vehicle

2.1. Heavy trucks

The factors are of different importance for different vehicles. Figures 8 and 9 taken from a report published by Linköping University [5] show an example for a heavy truck. The potential energy available in the "fossil fuel" is transferred into mechanical power available for the engine crankshaft. This available mechanical power is than used for mastering driveline, air drag and rolling resistance losses at a constant speed. The potential left over mechanical power is available for climbing and/or acceleration of the vehicle mass. In figure 8 a typical situation is presented for a 40-ton truck, driving at a constant speed of 80 km/h. Driveline loss accounts for 3%, air drag for 9%, rolling resistance for 12%. The left over mechanical power, 16%, is potentially available for climbing a slope and/or acceleration of the vehicle mass. Since the efficiency of the engine is only approximately 40%, the rolling resistance counts for about 12% of the total fuel consumption of the heavy truck.

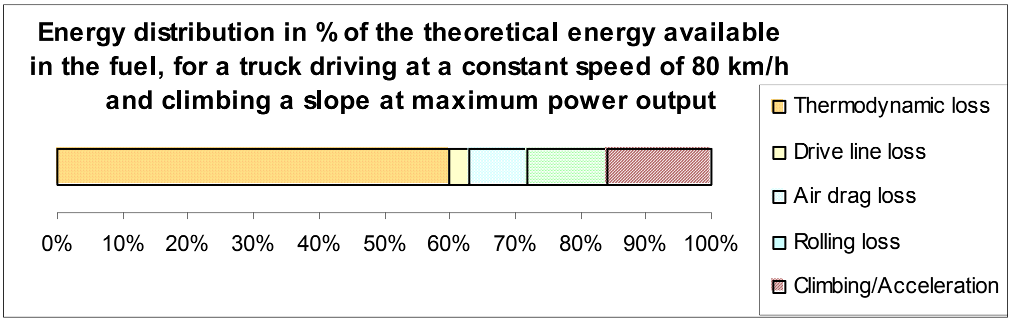

Figure 8 - Energy distribution of the potential energy available in the fuel

For a truck driving at a constant speed of 80 km/h and at maximum power output of the engine (Climbing/Acceleration means energy available for climbing a slope or accelerating the vehicle mass) [5] Linköping University

The same situation is presented again in figure 9 but now expressed as a percentage of the potential available mechanical power at the engine crankshaft. Driveline losses are now 7%, air drag 23% and rolling resistance 30%. Potential available for climbing and/or acceleration of the vehicle mass is 40% of the engine output mechanical power at the crankshaft. Reducing the rolling resistance loss can contribute significantly to the overall fuel need: the smoother the road, the lower the fuel consumption. [5] Linköping University

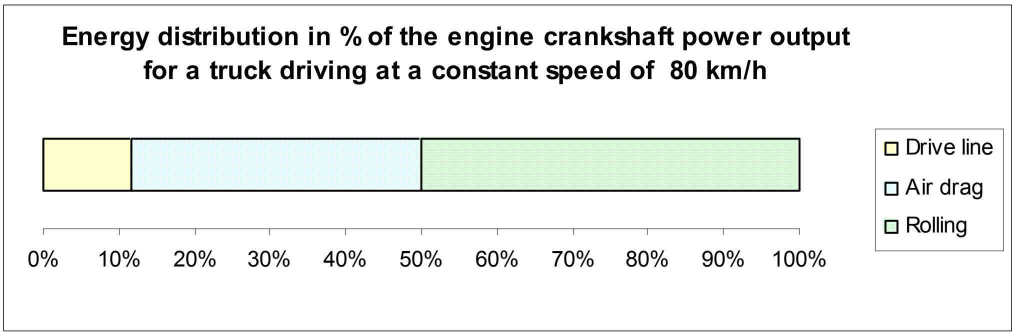

Figure 9 - Energy distribution of the actual power output of a heavy truck driving at a constant speed of 80 km/h on an even road. [5] Linköping University

2.2. Passenger cars

Figure 10 taken from a Michelin publication [6] shows how mechanical power available at the engine crankshaft is distributed as a function of the vehicle speed (no climbing, no acceleration).

At a constant speed of 100 km/h on a horizontal road, air drag represents 60% of energy loss while rolling resistance accounts for 25% and internal friction (drive line loss) for 15%. At higher speeds, air drag becomes the largely predominant factor.

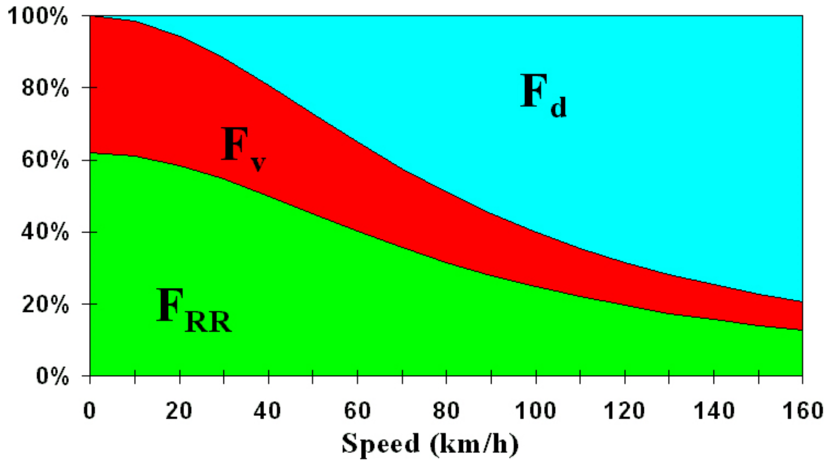

Figure 10 - Energy distribution in a passenger car versus speed as a percentage of the available power output at the crankshaft

Part of different forces as a function of speed for a passenger car:
Fd = Air drag, Fv = Internal friction and FRR = Rolling resistance

2.3. Conclusion 2

Approximately 12% of the fuel consumption for heavy trucks is accounted for by the rolling resistance losses in the tires at a constant speed of 80 km/h. This energy loss represents approximately 30% of the available mechanical power from the engine crankshaft.

Conclusion 3

For passenger cars driving at a constant speed of 100 km/h, the rolling resistance accounts for 25% of the available mechanical engine power output according to Michelin. Passenger cars are normally overpowered and therefore have less efficient running engines, in particular gasoline fuelled engines. As a percentage of the fossil fuel input it is estimated that rolling resistance losses account for 15 to 20% for such vehicles. At high speeds air drag becomes the largely predominant factor.

3. Factors influencing the rolling resistance

The definition of rolling resistance is that it represents the energy dissipated by the tyres per unit of distance travelled. One other way to express this is:

Tyre power loss = (Power input at the wheel axle) – (power output to the ground)

The rolling resistance depends both on how the tyre is designed (tyre factors) and on different characteristics in the road pavement.

Many different **tyre factors** influence the rolling resistance:

- Different shape of the tyre gives different rolling resistance at higher speeds.
- Higher air pressure in the tyre reduces rolling resistance.
- Higher vehicle load gives higher rolling resistance.
- The tyre manufacturers can change the composition of the tyres to achieve a lower rolling resistance.
- A higher ambient temperature reduces rolling resistance.

The type of road pavement and its surface also influence the rolling resistance. Different **surface characteristics** (pavement texture) provides a major contribution to the rolling resistance as does the **structural behaviour** as both bearing capacity and viscoelastic behaviour can influence the rolling resistance (see chapter 4).

At Mairepav'03 Symposium in July 2003 in Portugal, A. Woodside, University of Ulster, Northern Ireland, presented a paper about rolling resistance of surface materials affected by surface type, tyre load and inflation pressure [7]. In table 2 (from the paper) different factors affecting rolling resistance are presented.

Tyre characteristics	Tyre Operating Conditions	Environmental Conditions	Road Surface Characteristics
Construction: - cross ply - bias-belted - radial Tread: - compound - pattern - depth - fragmentation	Inflation pressure Load Speed Slip angle Camber angle Driving/braking force Wheel/axle configuration	Temperature Water Snow Ice	Micro-texture Macro-texture Mega-texture Unevenness

Table 2 - Factors affecting rolling resistance
Based on Woodside paper Mairepav'03 [7]

4. Impact of pavement surface characteristics

Road surface characteristics affect both the rolling resistance and the suspension losses. Both of these factors affect the fuel consumption. Road surface characteristics can be defined in terms of the following surface textures:

- *Microtexture* is the texture with wavelengths shorter than 0.5 mm
- *Macrotexture* is the texture with wavelengths in the range 0.5 to 50 mm
- *Megatexture* is the texture with wavelengths in the range 50 to 500 mm
- *Unevenness* is the "texture" or roughness with wavelengths longer than 500 mm

4.1. Study in Sweden

Published data on road surface effects on fuel consumption or rolling resistance have indicated significant influences of different textures. An experiment on the influence of road macro- and megatexture on fuel consumption has been performed by VTI (Swedish Road and Traffic Research Institute) in Sweden. The results of the study were published in ASTM STP 1031 in 1990 [8].

In the experiment a specially instrumented Volvo passenger car was run at 50, 60 and 70 km/h constant speed over 20 test sites with various surfaces textures. Macro- and megatexture as well as shorter wavelengths of unevenness were measured by a mobile laser profilometer. The fuel consumption data at each speed and averaged for the three speeds were regressed on the texture profile spectrum data. Some of the results from the experiment are shown in table 3.

Some of the conclusions in the report are:

- There is a clear correlation between fuel consumption and macrotexture and a very good correlation between fuel consumption and shortwave unevenness.
- An uneven road may increase fuel consumption by up to 12% relative to an even road.
- A rough macrotexture, not uncommon on Swedish roads, may increase fuel consumption by 7% relative to a very smooth macrotexture.
- Fuel consumption for a car may be influenced as much as 12% by road surface characteristics within the tested range.

- There are strong indications that there are three different sources of energy losses due to road surface effects:
- Vehicle suspension losses excited by the longest wavelengths
- Tyre-bulk vibration losses at wheel hop frequencies (at 0.5-1.3 m texture wavelength)
- Tyre impact hysteresis losses at the typical macrotexture wavelength (chipping sizes and spacing). The latter is pronounced only at 60 and 70 km/h and seems to be more important the higher the speed is.

Pavement type and aggregate size	**Texture data**				**Fuel consumption** [ml/10 km]		
	Micro scale*) 0 - 9	Macro L_{MA}**) dB	Mega L_{ME}**) dB	Short-wave unevenness L_{SU} **)dB	50 km/h	60 km/h	70 km/h
Dense Asphalt 0/8	6	48.0	45.0	54.4	695	676	736
Dense Asphalt 0/16	3	50.2	48.5	54.0	714	692	732
Cement concrete 0/25	2	52.0	56.3	58.6	720	710	756
Surface Dressing 4/8	7	53.9	50.2	56.1	696	701	781
Surface Dressing 12/16	6	63.9	60.5	58.8	708	725	788

*) Estimated microtexture on a scale 0 – 9 where 0 = perfectly smooth and polished and 9 = very harsh

**) The following wavelength ranges were used in the study:
- L_{MA}: level of macrotexture, range 2 to 50 mm
- L_{ME}: level of megatexture, range 63 to 500 mm
- L_{SU}: level of shortwave unevenness, range 0.63 to 3.15 m

Table 3 - Texture data and fuel consumption for different Pavement Types
The values are normalised with respect to speed and temperature. [8]

4.2. Study in the Netherlands

In another experiment in the Netherlands fuel consumption on different types of pavements was studied. A report has been published in Dutch [9]. In the experiment a specially instrumented Volvo V70 passenger car loaded with two persons and full fuel tank was run at 90 km/h constant speed over the test sections. The results of the experiment are shown in table 4.

Road surface type	Fuel consumption relative to Dense Asphalt Concrete 0/16 [%]
Dense Asphalt Concrete 0/16	0
Porous Asphalt 6/16	- 0.0 (± 3.5)
Stone Mastic Asphalt 0/6	+ 3.4 (± 3.6)
Double-layered Porous Asphalt 4/8 + 11/16*	+ 1.2 (± 3.3)
Cement Concrete, broomed transversely	+ 0.4 (± 3.4)
Cement Concrete treated with a surface epoxy durop	+ 2.7 (± 4.5)
Brick-layered pavement	+ 5.3 (± 6.6)

* New road surface; bitumen film still present

Table 4 - Fuel consumption at 90 km/h on different types of road pavement relative to Dense Asphalt Concrete 0/16
Mean value on long measuring sections, corrected to 20°C, weather without wind and a Volvo V70 passenger car loaded with two persons and full fuel tank. Between brackets it shows the 95% confidence level of the difference

Conclusions from this study are:

- There is no significant difference in fuel consumption found between porous and dense road surfaces. The positive and the negative effects, found in the literature, cancel one another roughly.
- From a statistical point of view there is no significant difference in fuel consumption found between asphalt and cement concrete road surfaces.

Additionally it was mentioned that dense road surfaces that are used in the Netherlands are for the greater part in the category fine textured road surfaces. The differences in fuel consumption that could be expected within this category are, according to the literature, up to 10%.

Another conclusion of the Dutch report was that the condition of the road surface especially those that influence the texture and the evenness (like the quality of the construction and the maintenance), seem to have a strong influence on the rolling resistance and therefore on the fuel consumption of the traffic driving on this road surface.

In these two experiments in Sweden and in the Netherlands only passenger cars were used to study the influence of different pavement textures on fuel consumption. Trucks were not used in the studies.

4.3. Study in USA

WesTrack is an accelerated pavement test facility constructed in Nevada in 1995 for the Federal Highway Administration (FHWA). The primary objectives of WesTrack are to continue the development of performance-related specifications for hot-mix asphalt pavement construction. Four driverless trucks were used at WesTrack for the pavement loading. Over 2½ years the driverless trucks travelled more than 1.3 million km. Throughout the loading period data were collected on a large number of vehicle parameters, including fuel consumption.

During the 2½-year loading period, pavement sections located on the track's tangents developed varying amounts of roughness, rutting and/or fatigue cracking. Some sections eventually required major rehabilitation. The vehicle and pavement data taken before and after the last rehabilitation were used to project the impact of pavement roughness on vehicle operating costs [10]. The data showed that rehabilitation reduced average IRI by at least 10%.

The data also showed that a decrease in pavement roughness decreased the fuel consumption of the trucks. Under otherwise identical conditions, trucks used 4.5% less fuel/km on smooth post-rehabilitation pavement than on rough pre-rehabilitation pavement.

4.4. Conclusion 4

*Different **textures** of road surfaces influence fuel consumption for passenger cars by up to 10%. There is no difference in fuel consumption between asphalt and concrete road surfaces for passenger cars.*

*Surface **roughness** has a proven huge influence on the fuel consumption and on noise development. Taken these aspects into consideration the total truck and passenger car population might easily result in an advantage in fuel consumption for asphalt pavements.*

5. Impact of structural behaviour: viscoelastic behaviour of asphalt pavement

5.1. Experimental approach

In an experiment conducted by NRC, National Research Council, in Canada the effect of pavement structure on fuel consumption for heavy trucks was studied [11]. The overall aim of the project was to measure heavy truck fuel consumption on a variety of highway pavement structures and under a variety of test conditions to determine the dependence of fuel use on pavement structure, pavement roughness, vehicle configuration, vehicle speed, vehicle load and ambient temperature.

In the experiment, tests were performed on two concrete, three asphalt and one composite (asphalt/concrete) pavements. Three sizes of trucks – tractor semitrailer, straight truck with tandem rear axle and B-train – were used.

The main results of the project are evident from the following taken from the conclusions of the report:

"1. Potentially statistically significant differences between the concrete and asphalt were measured for the heaviest and fastest test conditions, especially between concrete and Highway 417 Asphalt.

2. Using a linear fuel consumption model for a tractor semitrailer with respect to pavement temperature to estimate the percentage differences from a concrete pavement's performance at a variety of pavement temperatures, the following observations are made:

- *There was higher fuel consumption over all temperature ranges on Highway 417 asphalt compared to concrete pavement on Highway 440 for the fully loaded tractor semi-trailer at all test speeds averaging 11%, 8% and 6% at 100, 75 and 60 km/h respectively.*
- *There were inconsistent trends on all other pavements and load conditions with smaller differences from concrete values observed. No explanation of the cause of these differences was identified in the variables that were collected in this study."*

In a later report from Canada [12] some additional statistical analysis of fuel consumption data collected in the NCR project has been made. The result of this statistical work is that the higher fuel consumption on asphalt compared to concrete was corrected to 4.1 – 4.9% instead of 11% at 100 km/h. At 60 km/h the fuel consumption on asphalt was confirmed 5.4 – 6.9% higher than on concrete [6% in the original report].

The overall conclusion of the experiment performed by NRC in Canada [11, 12] is that there seem to be some differences in fuel consumption for asphalt and concrete pavements. But only one of the three asphalt test sections had higher fuel consumption than the concrete section. In this asphalt section the fuel consumption was between 4 and 7% higher than on the concrete section. The other two asphalt sections had the same fuel consumption as the concrete section. It was also only one of three load conditions that gave higher fuel consumption on asphalt pavement than on cement concrete pavement.

In the report from NRC [11, 12] a number of significant statistical limitations have been mentioned. This includes differences in surface roughness, large variation in air and pavement temperatures and short pavement test sections. Based on the limitations of the study, it is apparent that no validated conclusions can be drawn regarding fuel savings attributed to pavement type.

5.2. Theoretical approach

One of the fundamental laws in thermodynamics is that energy can not disappear into infinity. Higher fuel consumption necessarily must result in the development of heat. Design and evaluation software is available to calculate this so-called dissipated energy. With this software the theoretical maximum possible energy dissipation in asphalt pavement can be calculated under traffic conditions and compared to concrete pavement.

NPC, Netherlands Pavement Consultants have made a theoretical calculation [13] of the maximum energy dissipation when driving on asphalt pavement and when driving on rigid cement concrete. In the calculation NPC has used the linear visco-elastic multi-layer program VEROAD® developed at Delft University of Technology [14].

In the VEROAD® calculation the spring- and autumn air temperatures used was 16°C, and the summer temperature 26°C. This results in average pavement temperature ranges from 18.5 to 42°C. The material parameters in the study are taken from laboratory investigations. 100 and 130 kN axle load and 0.75 MPa tyre pressure have been used. The vehicle speeds have been 50 and 80 km/h.

For each loading condition four VEROAD® calculations have been made. The result of the study is evident from Table 5 taken from the report from NPC:

Time of the year	Axle load	Speed	Energy per dual tyre wheel per meter of road	Energy per axle per 100 km of road	Energy per vehicle per 100 km of road	Fuel per vehicle per 100 km (14 MJ/litre effective)
	[kN]	[km/h]	[J/m]	[MJ]	[MJ]	[litre]
Summer	100	50	5.21	1.04	3.34	0.24
Summer	100	80	3.52	0.70	2.25	0.16
Summer	130	50	6.96	1.39	4.46	0.32
Summer	130	80	4.76	0.95	3.05	0.22
Spring	130	50	1.27	0.25	0.81	0.06
Spring	130	80	0.93	0.19	0.60	0.04

Table 5 - Calculation of dissipated energy in asphalt pavement due to its viscous behaviour [13]

The conclusion in the NPC report is:

"The fuel consumption for an average 130 kN axle load truck, driving at 80 km/h is approximately 25 litres per 100 km. The maximum increase of fuel consumption caused by the visco-/elastic behaviour of asphalt pavement in comparison with rigid cement concrete pavement is:

- *In the spring and autumn approximately 0.16%*
- *In the summer (worst case: extreme hot day) approximately 0.88%*
- *On a yearly average it is estimated that less than 0,05% extra fuel consumption may exist for a truck driving on asphalt pavement."*

This means that the result from NRC experiment in Canada that fuel consumption for heavy trucks will increase by 4 to 7% when driving on asphalt pavement compared to concrete can not be confirmed. The possible difference is likely to be much less than 1%.

The results in the NPC report are also reinforced by a study at LCPC, France [15]. The scope of the study is the calculation of the rolling resistance of a rigid cylinder rolling on a homogeneous visco-elastic support. The result of this study shows that the rolling resistance calculated for a speed of 90 km per hour at 15 °C is equal to the tangent of the angle of 0.00036, which represents a slope of 0.036% (i.e. almost negligible: 36 cm for 1 km)

5.3. Conclusion 5

*Regarding **structural behaviour (viscoelasticity)** of asphalt and concrete pavements the conclusion is that there is no (or a negligible) difference in fuel consumption for heavy trucks driving on asphalt roads compared to concrete roads. On a yearly average it is estimated that less than 0.05% extra fuel consumption may exist for trucks driving on asphalt pavement.*

6. General conclusions

The results of different studies show that there are a lot of factors that influence the energy consumption and greenhouse gas emission for roads. It is therefore very difficult to get conclusive results from field experiments.

It is clear that during construction, maintenance and operation of roads the energy consumption and the greenhouse gas emissions are lower for asphalt than for concrete pavements. But it is the traffic on road that accounts for the major part (> 95 or 98% depending on traffic volume) of the total energy consumption and greenhouse gas emission, and here the differences between pavement types as such (asphalt or concrete) are not significant. More important for the fuel efficiency are pavements in good condition with good surface characteristics (texture and roughness). Optimal maintenance of the roads is therefore the means to limit fuel consumption and green house gas emission.

Besides energy consumption decision makers need also to consider several other factors in order to satisfy the multiple requirements of protecting the environment (limiting green house gas emission), saving energy, reducing traffic noise and ensuring good driving safety and comfort.

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