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CO_2 emission reduction by exploitation of rolling resistance modelling of pavements

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Abstract

Approximately one third of the Danish CO_2 emissions come from the transport sector, whereof 95% is related to road transport emission. A reduction of the fuel consumption by approximately 3.3 % on the road infrastructure will result in 48 million litres of saved fuel and 45.000 tons less greenhouse gases per year. Energy saving road pavements will therefore contribute to Denmark's quota in reaching the global climatic goals. The Cooee project addresses CO2 emission reduction by considering energy efficient and environmentally friendly transport systems and maintenance of the road infrastructure. By doing so, the Cooee consortium will exploit the research results in management of the Danish road infrastructure. To contribute to a sustainable Danish road infrastructure by reducing CO_2-emission in a cost-effective manner, Cooee addresses the following: 1. Novel pavements with low rolling resistance, 2. Models of rolling resistance, 3. Wear and ageing of pavements, 4. Measurements of rolling resistance, 5. Asset management systems. The Cooee project is a collaboration between the Danish Road Directorate, Roskilde University, the Technical University of Denmark and NCC Roads. The Danish Strategic Research Council granted in 2011 2 million EUR to the Cooee project. The Cooee project plans to create two models: A comprehensive model of the contact zone between the tyre and the pavement, and a model for the pavement material. When these are in place, performance and optimization models will be established and implemented in the Danish asset management system "vejman.dk". This will enable the Danish Road Directorate to include CO_2-emission as a parameter in its strategic planning and maintenance of the Danish state roads. This paper presents the outline of the project, its expected results and the status.

Keywords; pavements, CO_2 emission, rolling resistance, wear and ageing, measurements, asset management

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1. Introduction

The Cooee project, scheduled to run over four years (2011-2014), focuses on establishing the scientific background for novel pavement types and asset management solutions that minimise the rolling resistance for cars and trucks, the purpose being to reduce CO_2 emission from the transport sector. In 2006 the total Danish CO_2 emission was 52.5 million tons, of which the transport sector's share was 16 million ton, even a minor reduction of the rolling resistance leads to substantial energy savings and CO_2 emission reductions, as well as to the reduction of other pollutants coming from road transport. The Cooee project will contribute to a sustainable road infrastructure by integration of rolling resistance modelling in pavement maintenance systems. The project is ambitious and truly interdisciplinary, stretching from fundamental condensed-matter physics, over the science behind measurement and modelling of rolling resistance and new pavement types, to implementation via asset management systems.
The project's focus is on reducing the rolling resistance, but it is scientifically well established that pavements with low rolling resistance are also less noisy (ref.1); thus the Cooee project contributes to the creation of an overall more environmentally friendly road infrastructure.
One of the important issues to handle is the pavement material and its behaviour to wear and ageing. Because asphalt is a viscous material it is considered possible to use the most recent research results from viscous-liquid physics in describing ageing and wear of pavements. In order to arrive at a comprehensive modelling of pavement properties, research into new measurement techniques will be conducted. The results of the project will be incorporated into existing maintenance systems.
Due to the fact that PCC or concrete roads are very rarely used in Denmark, it has been decided to limit the Cooee project to asphalt materials. For example, the total amount of motorways in Denmark with concrete pavements consists of 10 – 15 km out of the 3789 km of state roads.
Internationally the difference between truck tyres and passenger tyres is discussed actively. The Cooee project does not distinguished between truck tyres and car types, but the project partners are aware of the fact that the large differences between the two tyre types, sizes and compounds may call for different approaches for the optimisation of rolling resistance properties.

2. Cooee structure

The Cooee project addresses the following five main subjects. The purpose of this structure is to develop and future-proof Danish road infrastructure systems by reducing CO_2 emission in a cost-effective manner.

1. Novel pavements
2. Models of rolling resistance
3. Wear and ageing of pavements
4. Measurements of rolling resistance
5. Asset management systems

Below we briefly review the objectives of each of the five subprojects.

3. Novel pavements

A key research objective of this effort is the creation of environmental friendly pavement materials, which provide safety and are economically feasible. The purpose is to develop sustainable asphalt pavements. The research aims at developing new asphalt materials that are able to resist the influence of mechanical and environmental wear and provide low rolling resistance without jeopardising fundamental requirements such as traffic safety and structural properties.

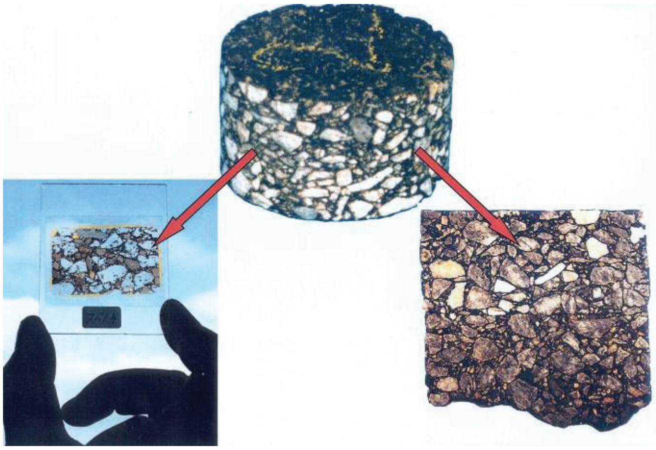

Figure 1, Thin and plane sections from an asphalt core.

When initiating fundamental research, it is important to establish a platform as a starting point. The platform for the potential materials to be studied in the novel pavement subproject is based on the following guiding principles. First and foremost it is believed that a pavement with low rolling resistance shall consist of small aggregate grain sizes in the order of 6 – 8 mm. However, one thing is to create a pavement with an initial low rolling resistance, which provides sufficient tyre/road grip and noise reduction etc.; the challenge is to create a road pavement that keeps these functionalities in its entire life time. This requires a stable grain size distribution and a very strong, ageing resistant mortar (filler and bitumen mix). The Cooee project regards the following parameters as vital for producing a long-life, low-rolling resistance pavement:

- Gradation curve
- Mortar composition
- Filler type
- Aggregate material > 2 mm
- Bitumen, type and quality

The initial recommendations are asphalt products with aggregates sizes 0/8 and 0/6.

The mortar part is just as important as the aggregate part, because the quality of the mortar is a determining factor for the stability of the asphalt product, which eliminates deformation. The mortar quality is also an important factor for obtaining a stable pavement surface structure. This means that the bonding between mortar and aggregate are strong and prevents ravelling and stone loss. Secondly, specific requirements for the aggregate strength must be defined to prevent aggregate polish.
The functionality of the asphalt by using small aggregate sizes and the requirements for the mortar must somehow be evaluated sufficiently before thinking of established actual test sections. Traditional laboratory investigations and analysis will therefore be used to investigate the quality of the mix. However, as it is of outmost importance to secure a correct aggregate distribution within the new

pavement type, visual and microscopic evaluation of the asphalt will be used using plan section and thin section analysis figure 1, (ref. 2).
Furthermore it must be considered how rolling resistance can be measured and justified on laboratory samples. Possibilities are to measure pavement texture by using laser technology. This requires a reliable correlation between texture and rolling resistance, which presently does not exists.
Experiences for relating texture to other functional properties of pavements such as noise and friction have shown that it can be difficult to obtain the needed and necessary relationships.

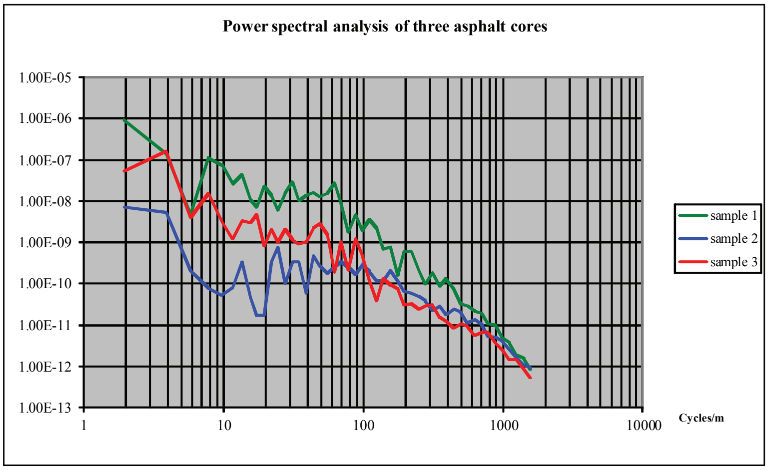

Figure 2, Power spectral density of three different asphalt surfaces. (ref.3)

In figure 2, the complexity of pavement texture is illustrated by calculating the power spectral density (PSD) of the texture profile for three different asphalt pavements. The figure clearly shows a ranking of the three samples when looking at the texture properties in the high texture 1- 100 cycles pr. meter. It is also interesting to notice that the ranking changes when moving up in frequency > 100 cycles pr meters, moving down in texture size. One of the fundamental questions to be answered is what part or what combination of texture has an influence on rolling resistance. The idea is that if texture can be optimised by a texture fingerprint as provided by PSD, it becomes possible to construct the most appropriate pavement for rolling resistance (still bearing in mind that other functionalities such as friction and noise are kept as well).

4. Models of rolling resistance

The objective of this subproject is to perform strategic research into investigating the main physics in the contact zone between the tyre and pavement surface. The fundamentals of tyre and pavement hysteresis, which depends on tyre hardness, tyre tread pattern, pavement texture and pavement structure and forces acting in the tyre pavement zone, will be part of a comprehensive model to be developed. The model will combine the structures at the molecular level with those at system level in order to optimise the parameters influencing rolling resistance. The research will include both new and worn tyres, because the tyre properties changes due to wear and age. It is assumed that the overall emitted CO_2 from the road transport is not linearly related to rolling resistance, but highly dependent on vehicle fleet, its type, age and condition, so the comprehensive model will include vehicle behaviour effect on the tyre/road interaction.

This project attempts to provide answers to:

- What parameters should be measured and with which accuracy and precision. This includes inflation pressure, tyre types (diameters and width) and loading range of the tyre
- What are the importance of air/tyre and surface temperature sensitivity and the influence of mega texture on the RR
- How to design a comprehensive mathematical model that includes all variables of more than minor importance on the RR

In order to make solid optimisation and user cost models it is important to model fuel consumption in relation to pavement properties. Therefore, a fuel consumption model will be developed. This model should include a number of different vehicle types and include new tyres and worn tyres, due to changes in tyre properties from wear and age.

Because the overall emitted CO_2 amount is not linearly related to rolling resistance and is highly dependent on vehicle type, age and condition, the fuel consumption model will include vehicle behaviour effect on the tyre/road interaction.

The modelling will consist of a number of fuel consumption models of varying complexity. Parameter estimation techniques (in particular Functional Data Analysis) will be used in order to relate the models to data.

Fundamental physics of the pavement and tyre, including tyre and pavement hysteresis depending on tyre hardness, tyre tread pattern, pavement texture and pavement evenness and forces acting within the tyre pavement zone will be used as the basis for the modelling of rolling resistance. We anticipate a series of models of increasing complexity. As far as possible the models will be based on first principles.

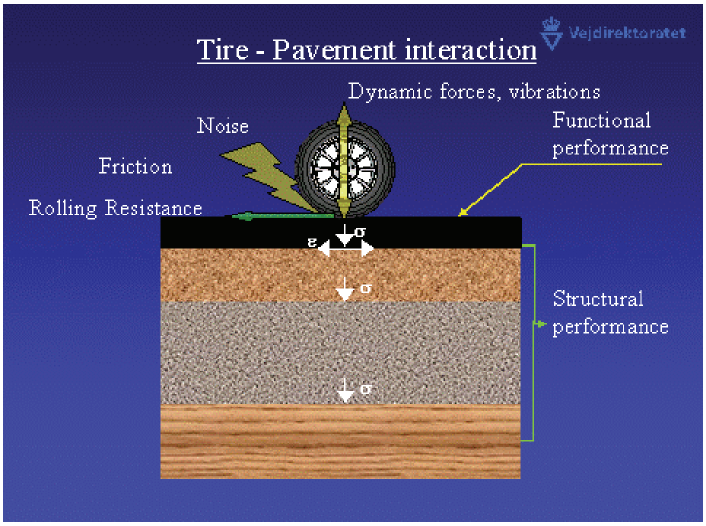

Figure 3, Interaction between pavement and vehicle

Figure 3, shows the different parameters interacting between vehicle and pavement. Rolling resistance is one of them, and from the projects point it will focus on pavement texture and partly on structural properties and performance. There are several discussions on the influence of structural condition on rolling resistance. In Denmark, where the rolling resistance issue is to be implemented on motorways and arterial main roads, the influence is considered marginal small compared to the texture influence. This is documented in ref. 4.

The EU project 'TYROSAFE' (ref. 5) reports that the predominant surface textures that influence rolling resistance are macro- and mega texture. It is known that deformation of the tyre is caused by variation in these two texture levels which leads to energy loss and therefore an increase in rolling resistance. Although much work has been put into what influences rolling resistance, there are still significant gaps of knowledge with regards to the influence of road surface parameters.

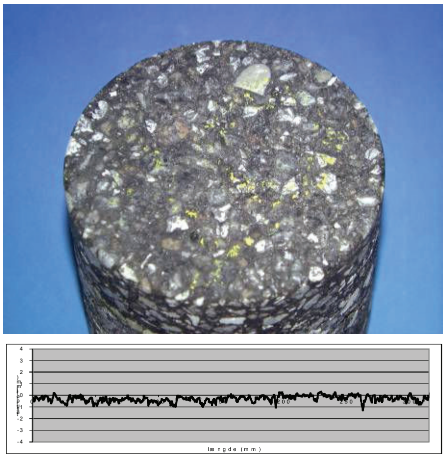

Figure 4, Road pavement with dense asphalt

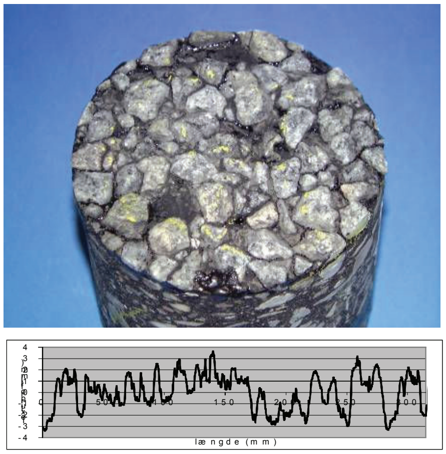

Figure 5, Road pavement with coarse surface dressing

As illustrated in figure 4 and 5 road pavements can have significant different texture profiles, which have different impact on the energy loss and thereof rolling resistance. The use of laser technology makes it possible to measure the texture profile very detailed in the laboratory. It is anticipated that the laboratory laser measurements of pavement texture can play a key role in the work of making a proper and correct modelling of the forces acting on the tyre from the pavement texture.

5. Wear and ageing of pavements

The condition of road pavements changes with time due to mechanical and environmental influences. This means that although the research conducted in novel pavements will create the best solution for low rolling resistance pavements, it is important to study the behaviour of these novel pavements in relation to wear and ageing. As the ageing of pavements are due to several years of deterioration and hence beyond the time frame of Cooee, accelerated ageing and modelling are considered to be the fundamental tools for researching the topics. The modelling of the pavement material will use the latest findings in ageing of materials. The model will be at the molecular level, but the simulated time frame will be years. The results of this research topic will be models that describe the performance of novel pavements with time, deterioration, and create the fundamental knowledge for establishing performance related models. These models can be used in asset management systems for road infrastructure, and hence play an important role when performing economic and environmental feasible solution for maintaining the road infrastructure.

The project will specifically address wear and ageing of asphalt pavements using computer simulations and modelling on several length and time scales. The first objective is to define a “Cooee-bitumen” molecular model suitable for large scale computer simulations, possibly in a few different versions. The model will be studied by simulating both thermal equilibrium dynamics and ageing.

Depending on discussions between all participants in the subproject there might be a few different Cooee-bitumen models and different additives to be considered. The bitumen model(s) will be validated against experimental results from literature and laboratory investigations.

One major task is to determine the required level of detail for molecular modelling of bitumen. A bitumen model from literature will be implemented and simulated in one or more coarse-grained version(s) using the Roskilde University Molecular Dynamics package (rumd.org) using state of the art GPU hardware. The results will be compared to the original all-atom version, and a sufficient level of coarse-graining will be determined. The level of coarse-graining will determine the length- and time-scales which can be accessed by simulation in the rest of the subproject.

In the second stage of the subproject the bitumen model(s) will be simulated in contact with aggregate surfaces mimicking the conditions in pavement with a special emphasis on wear and ageing. Mesoscopic modelling using finite element method or related will be used to determine the mechanical stresses on the surfaces of different pavements. One of the interesting questions to be asked in the wear and ageing project is: how do the models compare to reality? A tool that will be used in this connection is the thin-film analysis developed by the Danish Road Directorate. As seen in figure 6 (ref 1), it is now possible to detect stripping and other anomalies within the contact zone between aggregate and bitumen, which provides valuable information for evaluating the validity of the result from the modelling process.

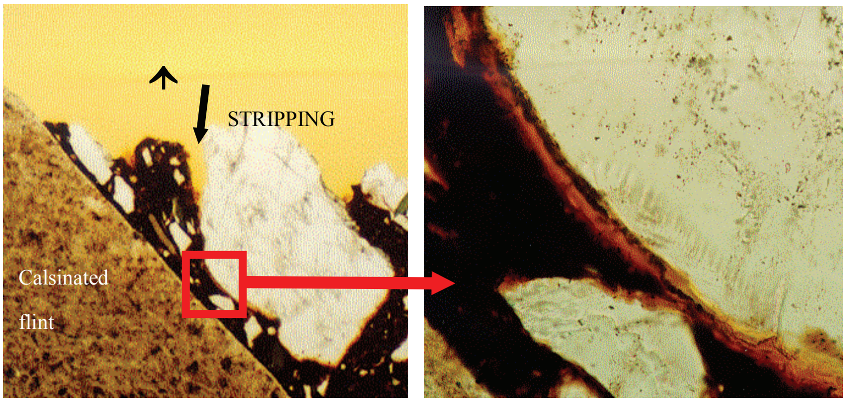

Figure 6, Detection of stripping, using thin film analysis

6. Measurement of rolling resistance

The objective is to design an equipment, that can be mounted on a trailer, which physically records the rolling resistance on existing pavement surfaces by measuring the vertical and horizontal forces.
An important issue is to measure and quantify the rolling resistance, preferable under dynamic conditions, in order to be able to monitor complete road infrastructure networks. The comprehensive model established in the research topic “Models for Rolling Resistance” will provide the fundamentals concerning the main physics of rolling resistance and guides the creation of reliable instruments for

measuring rolling resistance. The possibility of measuring rolling resistance under dynamic conditions is vital for being able to monitor true conditions of road infrastructure networks and hence a key point for establishing a system that can secure a reduction of CO_2 from the road infrastructure.

7. Asset management systems

The research topic will provide tools for asset management to handle rolling resistance and CO_2 emissions. The overall result anticipated in the project is a fully functioning asset management system, which includes the optimization of reduced CO_2 emission when new pavement types are introduced and which is capable of detecting solutions for an optimum maintenance and rehabilitation strategy for the road infrastructure. The implementation of technical and socio-economic methodologies in an asset management system is a complex task; therefore cost-benefit analyses including lifetime assessment (proving the percentage of CO_2 saved) will be carried out to relate costs of pavement construction and the effect of various maintenance solutions to the benefit expressed in less CO_2 emission.

First of all the requirements, design and specification of rolling resistance models to be implemented into the asset management systems, needs to be described.

The design of the deterioration model for pavements with low rolling resistance will be based on the outcome of the sub-project in Cooee, wear and ageing of pavements, and historical data of road pavement behaviour over time. These data will be obtained from the road databank of the Danish Road Directorate in relation to texture, evenness and bearing capacity (if available).

An important issue is the effect on rolling resistance and CO_2 emission by performing maintenance and rehabilitation of existing wearing courses using new pavement types with low rolling resistance properties. The design of a catalogue for novel pavement types is important in order to be able to perform correct optimization and cost effective analysis. The novel pavement type catalogue shall include type, rolling resistance information, lifetime and prize. The catalogue will be established in cooperation with sub-project on Novel pavements

The cost-benefit analysis based on CO_2 emission will be based on the NCC pre-study and the report “The energy saving road, Improving socio-economic condition by reducing rolling resistance” (ref. 6)

Also important LCA analysis is underway in the international MIRIAM project (http://miriam-co2.net/). These studies are mainly conducted at University of California – UCDavis. It will be investigated if results from the UCDavis studies can be calibrated to accommodate Danish conditions. (ref. 7)

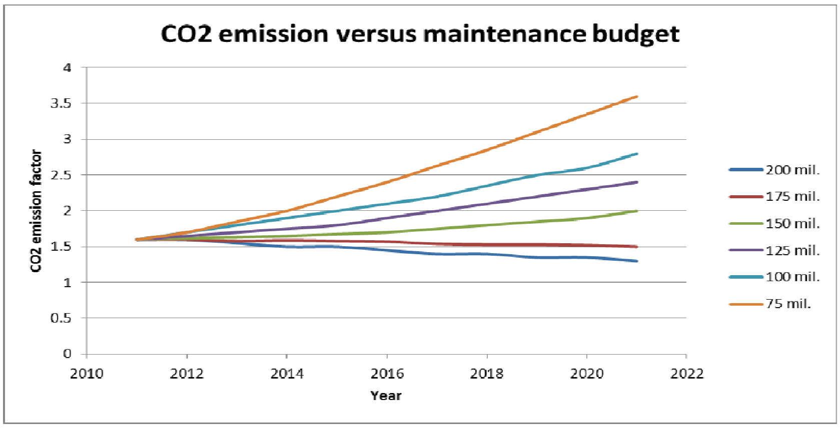

Figure 7, Relationship between CO_2 emission factor and maintenance budget (arbitrary currency)

The overall result of the Cooee project is for the Danish Road Directorate to forecast the CO_2 emission expressed in a factor depending on the maintenance and construction budget allocated for the state road network pr. year, as illustrated in figure 7. Figure 7, shows that with an increase in budget a reduction in the CO_2 factor is seen, and hence a reduction in CO_2 emission. This means that a very clear message can be send as to what budget needs be available for the administration in order to meet any requirement of reducing the CO_2 emission.

8. Results related to society

The significant contribution of rolling resistance comes from pavement roughness and pavement evenness, whereas the pavement roughness plays the most important role. This means that if a reduction of rolling resistance, and hence reduction in CO_2 emissions shall be achieved which will be the overall result related to the society, the road pavements shall be optimized in relation to roughness and evenness.

The international society of road research has specified rules thumbs for the relationship between rolling resistance and e.g. fuel consumption that says that a 10 % reduction in rolling resistance provides approximately a 3 % reduction in fuel consumption. International research as the European funded research project Energy Conservation in Road Pavement Design, Maintenance and Utilisation (ref. 8), specifies that changes in rolling resistance of up to 6 % and 30 % related to evenness and roughness, respectively, should be possible when optimising on these two road pavement parameters.

Combining the potential in rolling resistance savings with the relationship between rolling resistance and fuel consumption, there are significant benefits seen for a better environment by significant reductions in CO_2 emissions.

A recent investigation analysing the potential of savings on fuel consumption and on socio-economic aspects when introducing pavements with low rolling resistance, performed by the Danish Road Institute in collaboration with the Danish consulting company NIRAS and the Scandinavian contracting company NCC (ref. 6), showed that a reduction of fuel consumption by approximately 3.3 % is achievable if new road pavement design concepts are made available on the main road network in Denmark.

The research proposed within the Cooee project is expected to give a significant contribution to achieving this goal.

9. Concluding remarks

The Cooee project’s aim of designing a device for measuring rolling resistance is associated with the general impression that the existing devices have a rather low precision. If the inclusion of rolling resistance and fuel consumption in asset management systems shall have any form of validity, it is important to have correct and precise data of rolling resistance. This will result in a robust tool for handling CO_2 emission in road infrastructure asset management systems

The general impression is that pavement materials are not resistant to the influence of wear and environment if we look at traditional way of quantifying pavement behaviour. However, if the road transport sector is to provide services on all aspects in the future such as traffic safety, environmental impacts and comfort, taking increasing transport needs into account, it is time to look forward. The microstructure modelling to be performed within the Cooee project opens up new possibilities for the design of pavements and for understanding the mechanism behind deterioration. If successful, the information and results provided by Cooee will definitely benefit the international road transport community.

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