COOEE, CO2 EMISSION REDUCTION BY EXPLOITATION OF ROLLING RESISTANCE MODELLING OF PAVEMENTS

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ABSTRACT

The Danish Strategic Research Council granted in 2011 2 million EUR to the Cooee project to reduce road transport emissions of CO2 and nitrogen. The Cooee project is a collaboration be-tween the Danish Road Directorate, Roskilde University, the Technical University of Denmark, NCC Roads and Dynatest Ltd. The project will focus on rolling resistance and how to include rolling resistance in asset management systems. The project will contribute significantly to the international project MIRIAM (Models for rolling resistance in Road Infrastructure Asset Man-agement Systems) which was established in 2010 by 12 European and US partners.
As it is estimated that 25 percent of the CO2 emitted on the roads is caused by rolling resistance it is expected that 3-5% on fuel consumption can be saved by developing and implementing new low rolling resistance pavement types. A saving of 3 – 5% fuel is equivalent to at least 48 million litre of fuel saved annually in Denmark. That saving will provide 45,000 tons less green-house gases as CO2 and 76 tons less nitrogen oxides NOx in Denmark alone. Seen in a socio-economic perspective it will ideally be possible to save 40 million EUR in Denmark, when the expected output is implemented.
The project covers subjects as Novel pavements, wear and aging, models of rolling resistance, measuring rolling resistance and asset management systems.

The paper will describe the project in detail, status and expected outcome

Keywords: Energy, fuel consumption, novel pavements, wear, rolling resistance

INTRODUCTION

The overall objective of the Cooee project (http://cooee-co2.dk/) is to provide a sustainable and environmentally friendly road infrastructure. It will be done by developing an integrated methodology for improved control of the CO_2 emissions caused by the road transport during the service life of the road infrastructure. Although it is important to quantify and include construction and demolition in the overall CO_2 emission from the road infrastructure, this is not included in this work. The reason is that this is handled in many Life Cycle Assessment projects around the world one example is the international project on rolling resistance, MIRIAM, where this specific issue is handled by the University UCDavis, which is partner of the MIRIAM project(http://miriam-co2.net/)

The Danish Cooee project is an experimental and fundamental research project. The purpose is to develop new material types, creating a basic insight in wear and aging of asphalt pavement and fundamental research on the interphase between the vehicle tire and the pavement surface. It is importance to have an exact knowledge of the fundamentals before it is possible to make a generic system of rolling resistance models. The models shall be valuable for LCA and asset management systems taking fuel consumption and CO_2 emission into consideration.

The reason for initiating the Cooee project and the incentive for the Ministry of Research to fund the Cooee project was established in a pre-study performed by the Scandinavian contracting company NCC roads, The Danish Road Directorate, Dynatest and the Danish consulting company NIRAS (ref. 1). This pre-study analysed the potential fuel consumption savings and other socio-economic aspects associated with the introduction of pavements with low rolling resistance in Denmark. 3,817 km of Danish state roads were analysed representing approximately 5 % of the total road network in but carrying 45 % of the road traffic. The pre-study showed that a possible saving of 3 – 5% in fuel consumption is possible if pavements with low rolling resistance characteristics were introduced. A saving of 3 – 5 % in fuel consumption is in Denmark equivalent to an annual saving of at least 48 million litres of fuel. This amount of savings in fuel will provide an estimated saving of 45,000 tons less green-house gases as CO_2 and 76 tons less nitrogen oxides NOx in Denmark alone. Seen in a socio-economic perspective it will ideally be possible to save 40 million EUR in Denmark, when the expected output is implemented.

The Cooee project has been limited to asphalt materials due to the fact that PCC or concrete roads are very rarely used in Denmark. For example is the total amount of motorways in Denmark with concrete pavements 10 – 15 km out of the 3789 km of state roads.

Internationally the difference between truck tyres and passenger tyres is discussed.

The Cooee project does not distinguished between truck tyres and car types, but the project partners are aware the large differences between the two tyre types, size and compound may need different approaches for optimization of rolling resistance.

2 Rolling resistance and fuel consumption seen in a LCA context.

The life cycle phases of the road infrastructure include designing and constructing the different road pavements. This involves production of road materials, transporting the materials to the construction site etc. All this causes usage of fossil fuels and energy which leads to emission of CO_2 and GHG. Then on the far end of the pavement life cycle there is the end-of life challenges. The decision how to treat this part mainly depends on the overall road infrastructure strategy, which again depends on the actual and forecasted traffic flow and transportation needs. Are we to rehabilitate, widen, or make a complete new road? However, when we are looking at fuel consumption it is necessary always to consider the total fuel cycle emissions from construction to end-life, which also includes fuel consumption during traffic operation. One of the bigger challenges is how to quantify and produce solutions which can reduce the fuel consumption during the operation of the road infrastructure and how can we implement this in a LCA and thereof an asset management framework.

Important requirements to be established are the following:

- Pavement types which do not only have an initially low rolling resistance but keeps this for its entire lift time without losing other important pavement features (e.g. friction, evenness and durability)

- Robust construction and maintenance requirements that secures a long life functionality of the new pavement types.

During a pavements lifetime it is well known that deterioration occurs. This deterioration will increase rolling resistance, and result in lower fuel economy and increases the energy consumed. In order to be able to produce sufficient and reliable strategic planning it is important to be able to model the deterioration rate and to be able to calculate the correct and optimal time for maintenance and rehabilitation.

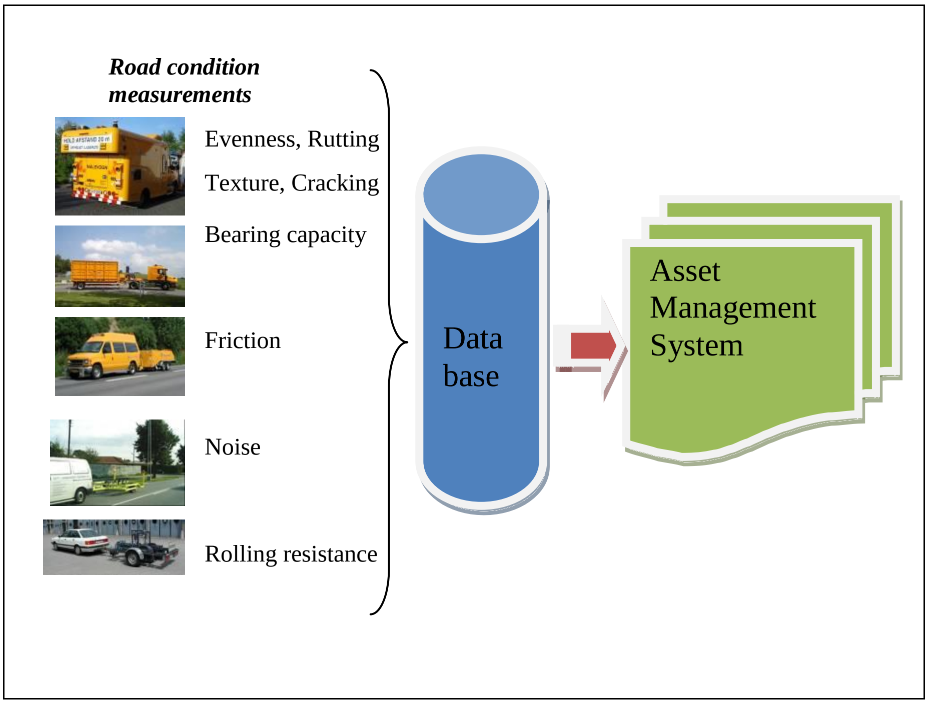

Figure 1, From data measurements to Asset management systems

When including new parameters in systems to manage pavement quality and condition these new parameters must be synchronised with already existing parameters and models. In Denmark pavement management systems has been in use for decades, meaning that already existing modelling of pavement deterioration has been the fundamentals for pavement rehabilitation strategies for many years providing a historic pavement construction and maintenance philosophy. Introducing new parameters will either change or supplement the philosophy.

The Cooee project will produce further insights into the relationship between pavement condition and fuel consumption.

a) The understanding of the relationship between pavement surface characteristics and vehicle fuel consumption will be investigated and developed.
b) The understanding of the influence of new pavement types on vehicle fuel consumption in relation to existing pavement types will be modelled and added in to the existing system of models.
c) Tire wear and damage to freight and vehicles due to the deterioration of pavement condition need to be determined.

The Cooee project consists of the following 5 different subprojects:

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

3.1 Novel pavement project

If we want to have success by introducing low rolling resistance pavements on the road infrastructure, it is important that we can create pavements that have the correct feature for reducing rolling resistance and, just as important, provide the service in its entire lifetime. Therefore, we are forced to be able to construct pavements with a durability that makes it last for at least as many years as the traditionally used pavements. When initiating fundamental research and investigating, it is important to establish a platform as a starting point. The starting point for the novel pavements project in Cooee is a pre-study performed in 2010 by NCC roads, The Danish Road Directorate, Dynatest and the NIRAS (ref. 1).
The pre-study (ref. 1 and 2) analysed the potential fuel consumption savings and other socio-economic aspects associated with the introduction of pavements with low rolling resistance, As the significant contribution of rolling resistance is associated with pavement texture and pavement evenness, it was necessary to decide on some reference values for MPD and IRI. The reference values were determined from the actual distribution of both MPD and IRI on the state road network as shown in figure 2 and 3.

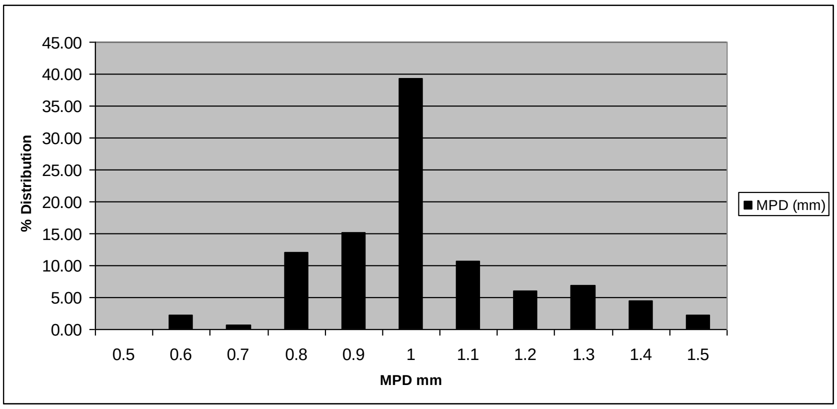

Figure 2: Distribution of MPD on Danish state roads

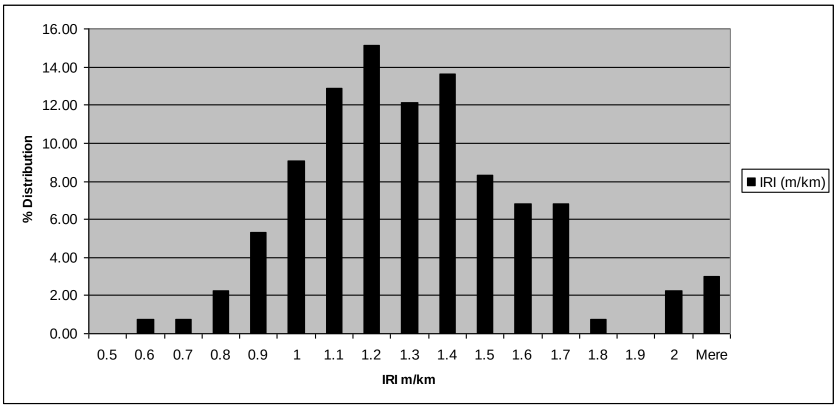

Figure 3: Distribution of IRI on Danish state roads.

Reference values of 0.6 mm (MPD) and 0.9 m/km (IRI) were selected. In selecting the reference value for MPD, it was recognised that skid resistance should not be compromised, as this is vital for maintaining traffic safety. Based on previous investigations at The Danish Road Institute (ref. 3), the MPD value of 0.6 mm was considered not to jeopardize traffic safety through a reduction in skid resistance. By using the specified reference or target values for both MPD and IRI the pre-study showed a predicted reduction in fuel consumption by approximately 3.3 % on the road infrastructure resulting in 48 million litres of saved fuel and 45.000 tons less greenhouse gases pr. year.

The big question or challenge for the novel pavements project is to find a solution for pavements that can provide the necessary target values over the entire pavement life time.

First and foremost it is believed that in order to produce a pavement with low rolling resistance one should choose a small aggregate grain size in e.g. the order of 6 – 8 mm. However, one thing is to create a pavement with an initial low rolling resistance which also lives up to other requirements such as tyre/road grip and noise etc. The challenge is to create a road pavement that keeps its functionalities in its entire life time. This requires a stable grain size distribution and a very strong, aging resistance mortar (filler and bitumen mix). The following parameters are considered as absolutely vital in order to produce 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 equally 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 to obtain a stable pavement surface structure. This is important when using small aggregate sizes which provide low texture properties of the pavement.

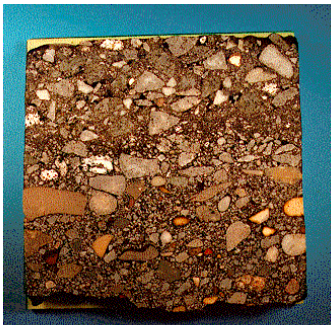

Figure 4, Plan section of an asphalt core

Figure 5, Thin section of asphalt

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, (figure 4), and thin section (figure 5) analysis. (ref. 4)
One of the more challenging parts by the creation of new pavement types which have low rolling resistance qualities is to measure the actual rolling resistance. Realizing that there are 3 devices available for measuring rolling resistance, using these devices requires actual test sections of a certain length not less than 100 meters.
However, the Danish Road institute has over the years performed several rolling resistance tests on test section constructed with focus on noise reduction. The results and experiences from these tests will be used as platform for creating the link between rolling resistance and mix design for developing the optimal low rolling resistance pavement.

3.2 Models of rolling resistance

The aim for modelling rolling resistance is to provide a tool for road infrastructure optimization and thereby providing important input to modelling rolling resistance in relation to pavement deterioration. In order to meet these goals a detailed design of the rolling resistance (RR) models will be designed
The project will determine on what parameters to be measured and with what accuracy and precision including parameters such as inflation pressure, tyre types (diameters and width) and loading range of the tyre.

In order to make the modelling of rolling resistance useful in an operational road infrastructure system, the models must also include a fuel consumption model. The relationship between rolling resistance and fuel consumption is important to be able to transfer the technical parameter rolling resistance to user cost. User cost plays an important role in the whole optimization process and hence are vital for be able to perform robust road infrastructure strategies.

Basically the modelling is to provide a model as illustrated in figure 6.

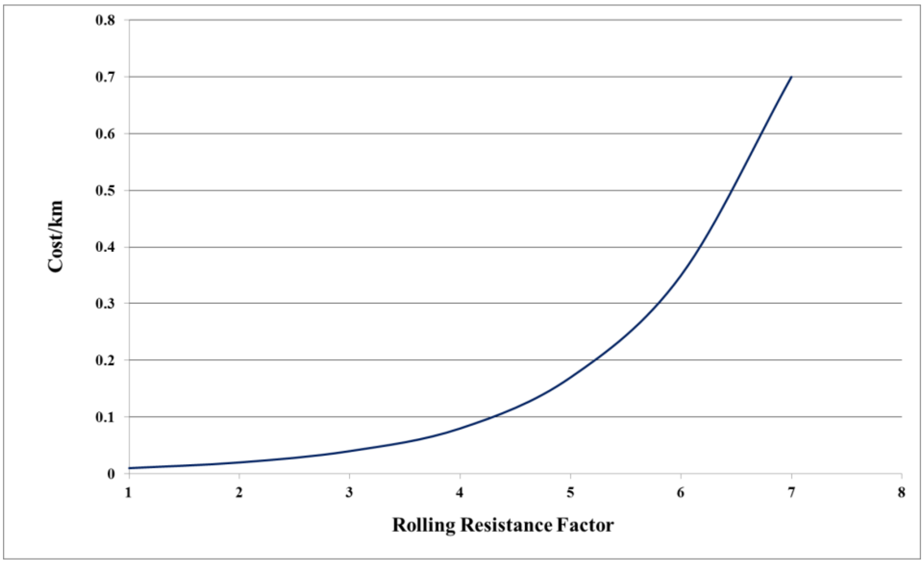

Figure 6, example of needed relationship between user cost/km and rolling resistance

The model illustrated in figure 6 should include a number of different vehicle types, new tyres and worn tyres. Since 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 also 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.

3.3 Wear and aging of pavements

If we are to meet our goals with Cooee to contribute to a sustainable environmental road infrastructure, it is vital that we are able to model and forecast the lifetime of the low rolling resistance pavements by modelling wear and aging. It is often seen that by introducing new initiatives for pavement types the wear and aging challenges are not fully met, this can often be related to the mix design or construction. The Cooee project has a goal of being on the forefront with regards to durability of the new pavement types to be designed in the novel pavements part of the project.
Because asphalt is a viscous material Cooee sees the possibility to use the most recent research results from viscous liquid physics in describing aging and wear of pavements.

The first objective of looking at wear and aging is to define what we call the "Cooee-bitumen" molecular model. This model will be studied by simulating equilibrium dynamics and aging. The project operates with the possibility that more than one model will evolve from this work. This or perhaps several of these models will be implemented and simulated in one or more coarse-grained versions using the Roskilde University Molecular Dynamics package (rumd.org). The results will be compared to the original all-atom version, and a sufficient level of coarse-graining will be determined. The bitumen model will, when established, be validated against experimental results from laboratory work.
Once the project has defined one or more novel pavements, these will be used as scenarios for the setups studied in the molecular modelling. Mesoscopic modelling using finite element method or related will be used to determine the mechanical stresses on the surfaces of different pavements.

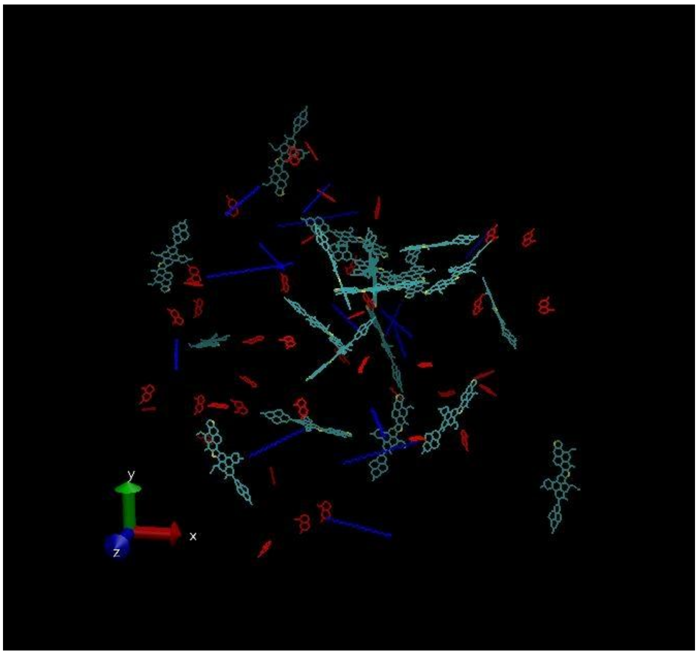

Figure 7; The first bitumen model from the Cooee project

Figure 7 shows the first bitumen model in the project. The model consists of three types of molecules, each of them representing molecules from real bitumen. In the figure 7 the following coloured figures are:

- Red; dimethylnaphtalen
- Cyan; an unnamed asphaltene which represents the larger grapheme parts in bitumen
- Blue; n-docosane

The model used is proposed by Zhang and Greenfield in 2007 (ref. 5). The Cooee project will continue working with the model trying to simplify it further. The original model is implemented in the Roskilde University Molecular Dynamics package which has the state-of the art graphics board which makes it possible to investigate different mechanism and aging processes, which have not been possible before.

3.4 Measurement of rolling resistance

Rolling resistance is the result of energy loss in the tyre pattern and the tyre sidewalls. Energy loss in the tyre pattern occurs as a result of hysteresis. Hysteresis occurs when the tyre pattern moves through the interface between the tyre and the road surface until it reaches the centre of the contact surface. At this stage, the stress is relieved as it travels from the centre to the rear edge of the contact surface. This, together with the energy loss associated with hysteresis in the tyre sidewalls, results in asymmetric pressure around the tread surface and greater pressure as it travels across the first half of the contact surface. The resulting force will therefore not occur in the centre of the contact surface, but instead just in front of it. The difference between the normal force on the tyre and the hysteresis force is the force that produces resistance against the forward movement, i.e. the rolling resistance.
This poses problems for measurement as these effects cannot be observed via traditional methods of tyre testing in laboratories on steel drums, having smooth and regular surfaces, as shown in figure 7.

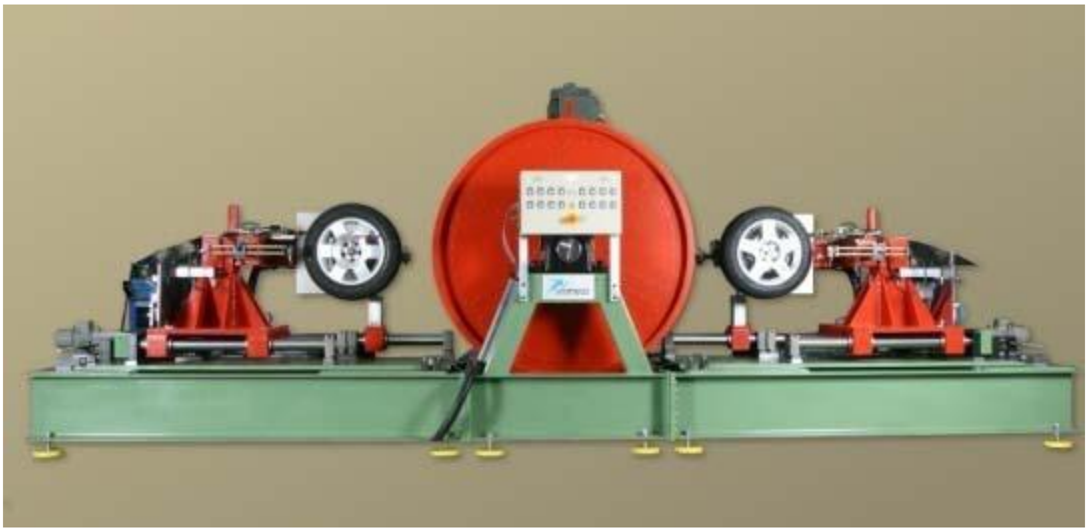

Fig.7: Steel drum test machine for tyre testing (ref. 6)

To date very little research has been published regarding the influence of the road surface on the rolling resistance of passenger car and heavy vehicle tyres. In Europe road surfaces are periodically inspected for skid resistance, surface profile and rolling noise emissions, but not for rolling resistance. As a result, the actual impact of the road on rolling resistance and the critical road surface parameters which influence rolling resistance are largely unknown. It is expected that parameters such as road surface texture (macro and mega-texture), surface layer stiffness, surface
temperature and longitudinal evenness may all influence rolling resistance to varying degrees
The '*Round Robin Test Rolling Resistance / Energy Consumption*, IPG - DWW Report 2005-046 (ref. 7) reports that rolling resistance can differ up to 15 % using the same tyres depending on the road surface texture. Several methods for measuring rolling resistance have been developed but no standards exist for the measurement of rolling resistance on a road pavement. Figure 8 shows the three existing methods for in service measurements during a MIRIAM test at the IFSTTAR facility in Nantes, France in July 2011.

Figure 8, Rolling resistance trailers testing at IFSTTAR in Nantes 2011. Photo by Dr. Ulf Sandberg

To address these knowledge gaps, robust methods of measuring rolling resistance in the field and laboratory are required. Although various methods, such as trailer methods, laboratory test on drums and coast down methods for measuring rolling resistance are available, the methods are associated with uncertainty whereof standards for testing are missing. The following are considered important for being able to make robust measurements of rolling resistance:

- the repeatability of rolling resistance measurements over short and medium term time frames
- the length of the test section for field tests, and the required number of test runs
- the optimum reference tyre to be used for field and/or laboratory measurements
- the effects of drum curvature for laboratory tests
- the effects of surface temperature, grade, tyre inflation, and travel speed

Realising the international view for the need to explore the possibility for in service rolling resistance measuring devices, the Cooee project takes up the challenge to design equipment that meet the requirements.

3.5 Asset Management

The overall result anticipated in the project is a full functioning asset management system, which includes the optimisation of reducing CO_2 emission through an optimum maintenance and rehabilitation strategy. 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 produce a lifecycle cost analysis (LCA) for rolling resistance and CO_2 emission. This will relate costs of pavement construction and maintenance solutions

to reduced user costs, expressed in less fuel consumption and CO_2 emission.
Novel pavement types and asset management solutions that reduce the rolling resistance for cars and trucks have until now not been included as contributing to energy reduction and to the global reduction of CO_2. The inclusion of rolling resistance models into asset management systems has a great potential for reducing the CO_2 emission. In 2006, the total CO_2 emission of Denmark was 52.5 million tons, of which the share of the transport sector was 16 million tons. The Cooee project will contribute to a sustainable road infrastructure through integration of rolling resistance modelling in pavement maintenance systems.

4 Conclusion

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 of outmost importance 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 possibilities seen from the microstructure modelling to be performed within the Cooee project open new possibilities for designing pavements and understand the mechanism which causes deterioration. The information and results provided by Cooee will be outstanding and will definitely benefit the international road transport community.

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