Rolling Resistance – Basic Information and State-of-the-Art on Measurement methods

Editor: Ulf Sandberg, Swedish National Road and Transport Research Institute (VTI)

List of contributors inside
DELIVERABLE #1 IN MIRIAM SP 1
Final version, updated 2011-06-01
List of contributors:

The order below is by alphabetical order of the authoring institutes (except in the case of the editor), and has nothing to do with the extent or importance of the contributions.

Ulf Sandberg
Swedish Road and Transport Research Institute (VTI), Linköping, Sweden
Editor and main author

Manfred Haider and Marco Conter
Austrian Institute of Technology (AIT), Vienna, Austria
Co-authors, contributors regarding definitions and models

Luc Goubert and Anneleen Bergiers
Belgian Road Research Centre (BRRC), Brussels, Belgium
Co-authors, contributors regarding the trailer method

Klaus-Peter Glaeser, Gernot Schwalbe and Marek Zöller
Federal Highway Research Institute (BASt), Bergisch-Gladbach, Germany
Co-authors, major contributors regarding laboratory drum and trailer methods

Olivier Boujard
Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (IFSTTAR), Nantes, France
Co-author, contributor with a French report about definitions, models and measurements

Ulf Hammarström
Swedish Road and Transport Research Institute (VTI), Linköping, Sweden
Co-author, major contributor regarding experience collected in the ECRPD project

Rune Karlsson
Swedish Road and Transport Research Institute (VTI), Linköping, Sweden
Co-author, major contributor regarding the coastdown method

Jerzy A. Ejsmont
Technical University of Gdansk (TUG), Gdansk, Poland
Co-author, major contributor regarding trailer methods

T. Wang and J.T. Harvey
University of California, Pavement Research Center, UC Davis and Berkeley, Davis, California, USA
Co-authors, major contributors with a North American literature review
Foreword

MIRIAM, an acronym for "Models for rolling resistance In Road Infrastructure Asset Management systems", is a project started by twelve partners from Europe and USA. They have collectively risen internal and external funding for this project. The managing partner is the Danish Road Institute.

The overall purpose of MIRIAM is to provide information useful for achieving a sustainable and environmentally friendly road infrastructure. In this project, the focus is on reducing the energy consumption due to the tyre/road interaction, by selection of pavements with lower rolling resistance – and hence lowering CO₂ emissions and increasing energy efficiency.

A first phase of the project will contribute with investigation of pavement characteristics, energy efficiency, modelling, and raising awareness of the project in order to secure economical and political support for a second phase. The second phase will focus on development and implementation of CO₂ controlling models into the road infrastructure asset management systems.

The website of MIRIAM is http://www.miriam-co2.net/ where extensive project information can be found.

MIRIAM has been divided into five sub-projects (SP), of which SP 1 is "Measurement methods and surface properties model".

This report is the first Deliverable in SP 1.
Acknowledgements and disclaimer

It is gratefully acknowledged that the production of this report has been funded by the following organizations (in alphabetical order):

- Austrian Institute of Technology (AIT)
- Belgian Road Research Centre (BRRC)
- California Department of Transportation (Caltrans)
- Danish Road Institute (DRI)
- Federal Highway Research Institute (BASt)
- Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (IFSTTAR)
- Swedish Road and Transport Research Institute (VTI)
- Swedish Transport Administration (STA)
- Technical University of Gdansk (TUG)

The funding organizations have no responsibility for the contents of this report. Only the authors are responsible for the contents. Any views expressed are views of the authors only.
TABLE OF CONTENTS

SUMMARY VII

1 INTRODUCTION 1

2 PURPOSE, LIMITATIONS AND CONCEPT 2

3 TERMINOLOGY AND DEFINITIONS 3

3.1 Energy consumption of vehicles in operation and its sources 3

3.2 Discussion of the concept of rolling resistance 5

3.3 Physical measures representing rolling resistance 6

3.4 The various contributors to rolling resistance and related mechanisms 7

3.4.1 Sources and mechanisms – general 7

3.4.2 Energy losses in tyres 7

3.4.3 Pavement-influencing tyre losses 9

3.4.4 Energy losses in pavements 11

3.4.5 Bearings 11

3.4.6 Tyre rotation aerodynamic losses 11

3.4.7 Tyre aerodynamic drag 11

3.4.8 Suspension 12

3.5 Problems with the present rolling resistance concept and measure 12

3.6 Discussion regarding measured contributions to energy losses and resistances with the methods employed in MIRIAM 12

3.7 Suggested terminology and definitions 13

4 VARIABLES AND PARAMETERS AFFECTING ROLLING RESISTANCE 17

4.1 Tyre properties 17

4.1.1 Tyre internal properties 17

4.1.2 Tyre external properties (dimensions) 17

4.1.3 Tyre speed category 19

4.1.4 Tyre rubber compound and rubber hardness 19

4.1.5 Tyre condition 20

4.1.6 Tyre rolling speed 21

4.1.7 Tyre load and inflation pressure 22

4.1.8 Tyre slip angle 22

4.2 Road properties 23

4.2.1 Texture and unevenness – old data 23

4.2.2 Texture and unevenness – new data 25

4.2.3 Microtexture 26

4.2.4 Stiffness and internal pavement losses 27

4.2.5 Road rutting, crossslope, curves and gradient 28

4.2.6 Road condition 28

4.2.7 Survey of rolling resistance of 40 Dutch test track surfaces 28

4.3 Bearing properties and condition 29

4.4 Suspension properties and condition 29

4.5 Temperature influence 31

5 ROLLING RESISTANCE CONTRIBUTION TO VEHICLE ENERGY CONSUMPTION 33

5.1 Introduction 33
6 REFLECTIONS AND OBSERVATIONS ON ROLLING RESISTANCE MEASUREMENT AND MODELLING FROM THE ECRPD PROJECT

6.1 Introduction and objective
6.2 Problems to address
6.3 What to include and not include in a tyre/road rolling resistance model

7 MEASUREMENT METHODS - GENERAL

7.1 Rolling resistance
7.2 Test objects: tyres or pavements?
7.3 Measurement of pavement-related parameters

8 MEASUREMENT METHODS – STANDARDS

8.1 Introduction
8.2 SAE
  8.2.1 SAE J1269: Rolling resistance measurement procedure for passenger car, light truck, and highway truck and bus tires
  8.2.2 SAE J2452: Stepwise coastdown methodology for measuring tire rolling resistance
8.3 ISO
  8.3.1 Past and present ISO standards
  8.3.2 ISO 18164:2005: Passenger car, truck, bus and motorcycle tyres — Methods of measuring rolling resistance
  8.3.3 ISO 28580:2009: Passenger car, truck and bus tyres — Methods of measuring rolling resistance — Single point test and correlation of measurement results
8.4 Other standards

9 MEASUREMENT METHODS AND EQUIPMENT – LABORATORY DRUM

9.1 Measurements at BASt, Germany
  9.1.1 General
  9.1.2 Description of the test procedure for rolling resistance measurements of truck tyres (procedure used at the PFF with the coastdown method)
  9.1.3 Description of the test procedure for rolling resistance measurements of passenger car tyres (procedure at the PFF with the direct force measurement)
9.2 Measurements at TÜV, Germany
9.3 Measurements at TUG, Poland
  9.3.1 General
  9.3.2 Measurement procedure
9.4 Drum surfaces
9.5 Effect of drum curvature
9.6 Measurements at ika / RWTH Aachen University, Germany
9.7 Laboratory facilities at other places

10 MEASUREMENT METHODS AND EQUIPMENT – TRAILER METHOD

10.1 General about the trailer method
10.2 The TUG trailer
10.3 The TUG measurement method
SUMMARY

MIRIAM has established a sub-project (SP), designated SP 1, to deal with measurement methods for rolling resistance and related issues. This subject forms the most fundamental basis for the MIRIAM ambition to consider rolling resistance in pavement management or other types of infrastructure systems. Without robust measurement methods and equipment that can use them there will be no reliable data as input to such systems and the end result will be most uncertain, if useful at all.

In order to develop and study measurement methods, there must be a basic understanding of the influencing parameters as well as what energy losses that should be included in the concept of rolling resistance. These issues are, therefore, important parts of the work in SP 1.

This report is intended to provide basic knowledge about the part of the tyre and road interaction which relates to rolling resistance; for example, the mechanisms that create rolling resistance, and the influence on rolling resistance of various tyre and road parameters. The intention is also to suggest a definition of rolling resistance for the purposes of this project, as well as to provide some detailed state-of-the-art knowledge about the measurement methods and equipment that are useful for collecting rolling resistance data.

It is first observed that rolling resistance is the result of an interaction between tyre and road surface, even including the deeper parts of the wearing course and the base layer. Therefore, tyres and road surfaces should not be tested without considering this interaction; thus using realistic (real) tyres and road surfaces. Although laboratory measurements are very convenient and desirable, such methods must always be based on validations made on real roads or test tracks.

Other major conclusions and recommendations are:

All kinds of rolling resistance measurements are complicated and subject to many potential problems and sources of errors

Tyre rolling resistance test methods, designed for tyres and standardized by ISO and SAE, lack consideration of realistic road surfaces

Standard test methods are available only for testing tyre rolling resistance in laboratories (SAE and ISO methods)

Standard methods for testing rolling resistance related to road pavements must be developed

Road parameters that clearly affect rolling resistance include MPD and IRI

There are indications that also pavement stiffness is a factor that must be considered

There are microslippage (stick-slip) effects in the tyre/road interaction that calls for consideration also of road surface microtexture (dry and wet friction)

Road surface conditions, such as rutting, wetness (water depth) and snow cover affect rolling resistance

For road management purposes one cannot rely on direct measurements of rolling resistance; it is better to develop a model by which rolling resistance can be predicted from collected road pavement data, the latter of which is already made to a large extent in many European countries

A tyre/road interaction model for rolling resistance must include a great number of road pavements, conditions and geometrical parameters
Two main methods are used for testing rolling resistance related to road pavements: the trailer method and the coastdown method.

MIRIAM has access to three different trailers for car tyres and one for truck tyres. All of them have unique features which are not fully compatible. It is recommended to conduct one or more round robin tests to compare these devices and methods.

There is a lack of reference surfaces for rolling resistance measurements of tyres and reference tyres for rolling resistance measurements of road surfaces. It is recommended to work out specifications for such in MIRIAM. One may then start by considering the use of the same reference tyres and reference surface as used for noise as one possible option.
1 INTRODUCTION

In 1979, a report of the French Ministry of Transport established that less than 10 % of the annual energy spent in the road field was used for construction and maintenance of infrastructures and more than 90 % was consumed by users of the same infrastructure; i.e. mainly by the road traffic [Anon., 1979]. Similar conclusions were drawn by the Energy Conservation in Road Pavement Design (ECRPD) project much later [ECRPD, 2010]. This suggests that an investment on road construction and maintenance, that has a substantial effect on road user costs, has a potential to give a very positive return for society. If this return is positive not only in monetary terms but also in environmental terms, the benefits of such investments may be substantial.

As expressed in the foreword, project MIRIAM has identified pavement rolling resistance properties as having a favourable potential for turning a small or moderate investment in pavement construction into a huge benefit for society in both economic and environmental terms.

A major purpose with project MIRIAM is to develop a model that will describe the effect of pavement surface properties on energy consumption and CO₂ emissions and, further, to make the data from the model useful in pavement management systems with a view to more effectively reduce energy consumption in road transport. This requires relevant and reasonably accurate data about the rolling resistance of the tyre/road system. Such data will be available only if there are robust measurement methods to collect them. These methods must be relevant for their purpose, repeatable, reproducible and accurate; and also reasonably practical to use. Usually, such methods are defined and described in measurement standards; preferably international standards, as only international methods will have a wide acceptance.

The present situation is that there are international methods (ISO), and also some industry-related methods (SAE), for measurement of the rolling resistance properties of tyres. These are indoor laboratory methods in which tyres are rolled on drums having an extremely smooth surface. For outdoor use and with the purpose to measure the rolling resistance properties of road surfaces, there is no standard method available. Consequently, there are no standards or widely accepted methods available for collecting the rolling resistance data of road surfaces that are needed as an input for pavement managing systems. Further, there is no knowledge about how representative the laboratory drum measurements according to ISO and SAE are in relation to road conditions with the various textures and unevenness that naturally exist on roads, which is totally different from the ideal smooth steel or sandpaper surfaces used in accordance with the present standards.

Therefore, MIRIAM has established a sub-project (SP), designated SP 1, to deal with measurement methods for rolling resistance, and related issues. This subject forms the most fundamental basis for the MIRIAM ambition to consider rolling resistance in pavement management or other types of infrastructure systems. Without robust measurement methods and equipment that can use them there will be no reliable data as input to such systems and the end result will be most uncertain, if useful at all.

In order to develop and study measurement methods, there must be a basic understanding of the influencing parameters as well as what energy losses that should be included in the concept of rolling resistance. These issues are, therefore, important parts of the work in SP 1.

This report is intended to provide basic knowledge about the influence on rolling resistance of various parameters, suggest a definition of rolling resistance and provide some detailed state-of-the-art knowledge about the measurement methods and equipment that are useful for collecting rolling resistance data.
2 PURPOSE, LIMITATIONS AND CONCEPT

The *purpose* of this report is fourfold:

- to provide a review and discussion of terminology and definitions, ending in a suggested definition with regard to rolling resistance of tyres interacting with pavements
- to provide basic and up-to-date knowledge about the influence on rolling resistance of various parameters
- to provide a comprehensive review and discussion with regard to measurement methods, and
- to provide a comprehensive review of available measurement equipment; especially of potential use in MIRIAM.

Other issues than those listed above are treated here only in a condensed form, with the aim to give a basic background for the measurement methods.

It is very important to note that rolling resistance is an interaction between tyre and road, although for the purpose of serving MIRIAM, this project has its focus on the road surface contribution.

The *concept* behind this report is the following:

- Rolling resistance is one of the most important functional properties of road pavements, applicable to the entire road network, which means that road authorities need to have information about it and be able to control it
- The relative importance of rolling resistance is increasing with time as it affects our energy consumption and the emission of greenhouse gases, while newer vehicle technologies such as electric and hybrid vehicles are more sensitive to this parameter than the present vehicle fleet
- The measurement of rolling resistance is very difficult and requires the use of rather advanced equipment and methodology, operated by very skilled and experienced staff; consequently, direct measurement of rolling resistance is possible only on a very small part of the road network
- A more practical way of controlling rolling resistance for road management purposes than directly measuring it, is to predict it from road pavement parameters that are already collected for most of the road network, such as texture, unevenness, stiffness and road topography
- Therefore, this report has a focus on rolling resistance modelling and related issues
- For modelling purposes this report includes large sections on generation of rolling resistance, tyre and road interaction, road pavement parameter influence and collection of data necessary to model rolling resistance based on the relevant road pavement parameters
3 TERMINOLOGY AND DEFINITIONS

3.1 Energy consumption of vehicles in operation and its sources

The movement of road vehicles requires that the power unit(s) of the vehicle overcome the "resistance to movement" which is due to the following forces [Michelin, 2003]:

- rolling resistance forces
- aerodynamic forces
- inertial forces (when accelerating)
- internal frictional forces
- gravitational forces (driving in slopes)

An illustration is shown in Figure 3.1.

![Figure 3.1: The various forces acting on the vehicle, which must be overcome to keep the vehicle moving. Illustration by kind courtesy of Mr Stefan Köppen of Goodyear [Köppen, 2009] (not yet granted).](image)

In this report, we prefer to use the term "driving resistance" instead of the longer "resistance to movement". A slightly different description of "driving resistance" is presented in [Hammarström et al, 2009] as the sum of the following:

- rolling resistance
- air resistance
- inertial resistance
- gradient resistance
- side force resistance
- transmission losses
- losses from the use of auxiliary equipment
- engine friction
Here, gradient resistance is the same as gravitational forces in the Michelin definition, and transmission losses and engine friction corresponds to internal frictional forces. Side forces (driving in curves) are not mentioned in the Michelin list, but are probably assumed to be counted as part of rolling resistance as they are essentially appearing in the tyres. Losses from using auxiliary equipment (fans, generator, servos, air condition, radio, cd player, etc) are neglected in the Michelin list.

Neither of the lists above mentions shock absorber losses in the vehicle suspension system. Such losses are far from negligible on real roads. Possibly, they might be included in the term “internal friction” used by Michelin.

Based on the discussion above, and with the aim of not mixing forces, losses and resistance, in this report it is suggested to divide the driving resistance into the following parts (with some explaining terms added in Italics):

- rolling resistance (forces opposing the rolling of the tyres)
- side force resistance, an extra contribution to the rolling resistance (sideway forces when driving in curves or poorly adjusted camber angle)
- suspension resistance (forces needed to overcome the frictional losses in the shock absorbers and pumping oil through small valves between different chambers (heating))
- aerodynamic resistance (also called aerodynamic drag or simply air drag; forces opposing the movement of the vehicle through the air)
- inertial resistance (forces opposing the acceleration of the vehicle, the product of acceleration and vehicle mass, or braking forces when decelerating, or forces from accelerating or decelerating rotating vehicle masses, especially during urban driving)
- gravitational resistance (forces needed to overcome driving uphill or released when driving downhill)
- transmission resistance, includes one part which rotates with the engine and another part which rotates with the tyres, separated by means of a clutch or corresponding component (forces needed to overcome the frictional or inertial losses in the transmission system (drive train))
- engine resistance (forces needed to overcome the frictional or inertial losses in the engine) (includes many subcomponents)
- auxiliary equipment resistance (forces needed to overcome the power consumed by vehicle equipment such as fans, generator, servos, air condition, radio, CD player, etc)

The side forces would also include the forces on the tyre when driving on the edge of a rut in the pavement. It may also be argued that side forces and/or suspension resistance should be part of rolling resistance rather than separate items. A discussion of these and other issues related to definition of rolling resistance follows in the coming sections.

To overcome the driving resistance, the engine (or electric motors in case of electric vehicles) must deliver a power which is converted from the energy contained in the fuel or the battery.

The driving resistance is influenced by numerous effects, some of which can also in turn be influenced by the design of the road infrastructure. For example, longitudinal unevenness of the road will induce suspension losses and influence the energy consumption. Gravitational resistance is related to the layout of the road in the vertical dimension while side force resistance depends on the road layout in the horizontal dimension. In mountainous regions gradient resistance, and also side force resistance (serpentine-shaped road layouts), can easily become the dominant components of driving resistance. Moreover, the road layout
governs the possible speed patterns and driver reactions, which in turn determine the level of tyre/road interaction effects and consequently rolling resistance.

The overall driving resistance system is more complicated than may seem apparent from the list above, since many of the various resistance components interact with each other, and some of them, for example air drag, are even non-linear. Any model describing the system, therefore, becomes complicated.

3.2 Discussion of the concept of rolling resistance

A very elegant illustration and description of how rolling resistance is created, either as a force acting opposite to the tyre movement along the road surface, or as a torque acting opposite to the tyre rotation, appears on page 12 in [Michelin, 2003]. Due to copyrights this cannot be reproduced here.

Rolling resistance has historically been considered as a force that opposes a tyre travelling in a particular direction. As pointed out in The Pneumatic Tire, a book commissioned and published by the US National Highway Traffic Safety Administration (NHTSA), some researchers find this concept unsatisfactory when a tyre rolls on a non-flat surface [Gent et al, 2005]. In the book by Gent et al, rolling resistance is defined as:

“... the effort required to keep a given tire rolling. ... Rolling resistance includes mechanical energy losses due to aerodynamic drag associated with rolling, friction between the tire and road and between the tire and rim, and energy losses taking place within the structure of the tire.” [Page 514]

From this point of view, rolling resistance is more appropriately defined in terms of energy, because many of its components are energy-related. For example, Schuring defines rolling resistance as a loss of mechanical energy [Schuring, 1977]:

“Rolling [resistance] is the mechanical energy converted into heat by a tire moving for a unit distance on the roadway.” [Page 31]

It is also emphasized in The Pneumatic Tire that rolling resistance is often calculated from the tyre-operating and shape parameters and cannot correspond to an actual physical force, so it should be measured as energy loss per distance travelled [Gent et al, 2005]. This conception is advantageous because it reflects the true situation in vehicles and it is directly related to vehicle fuel efficiency. Although the units used to define rolling resistance in these two systems are dimensionally equivalent (Newton versus Joule/Meter), Joule/Meter is more appropriate because rolling resistance is an energy (scalar) not a force (vector) [Schuring & Futamura, 1990].

This energy-based definition for rolling resistance is reflected in recent test standards, such as SAE J2452 and ISO 28580:2009 where rolling resistance is defined as the energy loss per distance travelled. In ISO 28580 rolling resistance (RR) is defined as "Loss of energy (or energy consumed) per unit of distance travelled" [ISO 28580, 2009]. Although not clearly expressed, it is assumed that it is intended that the losses concerned are losses occurring only in the tyres, as this standard is part of a series of tyre standards. Apart from losses in the tyre itself there are certain losses which occur very close to the tyre and which are difficult to distinguish from clear tyre losses when making measurements. These are called "parasitic losses".

Rolling resistance is caused by an interaction between tyre and road and therefore it is necessary to take both parts into consideration. In the SAE and ISO standards, this matter is neglected as testing is made either on a smooth steel drum or such a surface covered with sand paper.

Road surface texture creates local deflections in the tyre which causes extra energy losses in the tyre if the tyre rubber is not free of hysteresis. In extreme cases, this texture effect may
be equally large as the energy losses in the tyre measured on a flat and completely smooth surface. Some rolling losses are even consumed in the road or pavement rather than in the tyre; a fact which is totally neglected in the mentioned standards. Stones in the road surface may move a little tangentially under the forces of the tyre and the surface may deflect somewhat vertically (or rather radially) under the tyre load; two types of deflection which consume some energy if they are not totally elastic.

If the ISO definition is accepted, it would (probably unintendedly?) include also the aerodynamic resistance of the tyre, as this resistance creates a loss of energy related to the tyre. The physical dimension of the tyre would then be the important factor; especially the width and height/radius. This is a part of the total losses due to the tyres which is far from negligible at high speeds. However, the SAE and ISO standards do not take such losses into account; despite they would fall within the definition. Measuring this effect in connection with a laboratory drum facility would require some sort of extra wind tunnel.

From a road engineering point of view, an effect of the road surface is the vertical or near vertical vibrations of the tyre/wheel/suspension assembly caused by road unevenness. The energy losses from this may to some extent occur due to extra deflections in the tyre, but more so as energy conversion (to heat) in the shock absorbers. With certain measurement methods it is difficult to separate the shock absorber losses from the rolling resistance losses and some might argue that it is practical and justified to include shock absorber losses into rolling resistance as it is caused by the tyre rolling action. It would not occur without rolling. Unfortunately, the same applies to parts of the transmission in a vehicle. More about this will follow below.

The list of various driving resistances in 3.2 may equally well be transformed to a list of corresponding energy losses, related to the same phenomena, should one prefer to use energy rather than forces to define driving resistances.

### 3.3 Physical measures representing rolling resistance

A practical definition of rolling resistance must consider what kind of physical measure that can be used to measure this variable.

Energy does not appear to be a practical physical measure to use in an RR measurement standard. For example, measuring heat dissipation in a tyre, although not impossible, seems impractical.

The most relevant measure, also practical to use, seems to be something based on the force \( F_r \) that is required to move the rolling tyre in the desired direction. However, it is clear that this force will depend on the load that is applied to the wheel and thus the tyre.

Studies have found an approximately linear relation between rolling resistance and wheel load, represented by a force \( F_z \) (equal to the mass \( m \) of the load times the gravitational constant \( g \)). Since wheel loads can vary under different conditions, a near-constant coefficient, rolling resistance coefficient, RRC or \( Cr \) (both terms are commonly used), has been created to represent the characteristic of tyre/road rolling resistance: the dimensionless ratio of rolling resistance to wheel load: \( RRC = Cr = F_r/F_z \). ISO 28580 uses the notion \( Cr \).

Thus:

\[
\text{Rolling resistance coefficient (RRC)} = Cr = \frac{F_r}{F_z}
\]

where the forces \( F_r \) and \( F_z \) (see the preceding paragraphs) are magnitudes and not vectors.

This coefficient in turn depends on several tyre and road surface parameters as well as (to some extent) the vehicle speed. It is important to note that the RRC or \( Cr \) is a relative measure. It can be used to compare tyres and pavements.
Typical values of Cr for tyres in new condition are in the range 0.006 to 0.015 for passenger car tyres, and 0.004 to 0.012 for heavy truck tyres [FEHRL, 2006-1][FEHRL, 2006-2]. It is substantially lower for heavy vehicle tyres than for light vehicle tyres, not the least due to the higher inflation.

3.4 The various contributors to rolling resistance and related mechanisms

3.4.1 Sources and mechanisms – general

In and around the tyre there are several types of energy losses. The following is an attempt to list those which are of interest:

- Tyre losses (due to the tyre/road interaction; several mechanisms)
- Pavement losses (in the pavement itself)
- Bearing frictional losses
- Tyre rotational aerodynamic resistance
- Tyre drag (aerodynamic resistance when moving through the air)
- Suspension losses

As mentioned above, rolling resistance (RR) is defined by ISO as "Loss of energy (or energy consumed) per unit of distance travelled" [ISO 28580, 2009]. This standard also defines a family of energy losses called "Parasitic losses" as: "Loss of energy (or energy consumed) per unit of distance excluding internal tyre losses, and attributable to aerodynamic loss of the different rotating elements of the test equipment, bearing friction and other sources of systematic loss which may be inherent in the measurement." These, which are present but unwanted in measurements according to ISO 28580, include the following losses:

- tyre spindle friction
- measurement drum aerodynamic and bearing losses
- tyre and wheel aerodynamic losses (due to air pulled around by the rotating tyre in the still surrounding air)
- bearing friction (bearing between wheel and axle)

The two first ones are special to the drum measurement method; the two last ones are more general.

3.4.2 Energy losses in tyres

The rolling resistance is caused by the deflection and deformation of the tyre during the rolling and the hysteresis of tyre rubber and tyre structure. Rubber compounds exhibit a combination of viscous and elastic behaviour: they are visco-elastic materials. Each time rubber elements are deformed due to some force, if they do not entirely recover their original shape, i.e. if they are not totally elastic, they dissipate energy (heat). When a load is removed some of its stored energy is recovered while the rest is converted to heat, which creates energy loss. The lack of recovery is known as a hysteresis effect, as illustrated in Figure 2. The area enclosed in the loop is known as hysteretic losses. Rubber compound, tyre construction and tyre operation affect the hysteresis property of tyres.

Rubber behaves like a gas. When a rubber band is stretched it heats up. When it is released, the rubber cools down. There is, therefore, a hysteresis component from the thermal exchange with the ambient environment and another hysteresis component due to internal friction within the rubber1.

1 http://en.wikipedia.org/wiki/Hysteresis#Elastic_hysteresis
For a pneumatic tyre, the tyre load is mainly carried by the air contained in the tyre; and to a much lesser extent by the tyre structure. When the tyre is loaded onto a flat surface, the contact area is flattened, and the edges of the contact patch are deformed from their unloaded shape according to the flexibility and stiffness of the rubber tread, the tyre sidewall and the internal tyre structure. The most dramatic deformations occur in the leading and trailing edges of the contact patch. In addition, parts of the tread rubber are compressed and expanded, and exposed to stick-slip motions in the contact patch.

The different types of tyre deflection and energy losses which occur are as follows (see also Fig. 3.3 which illustrates most of the mechanisms):

- The loading of the tyre will make the contact patch essentially flat; with a very abrupt change of the shape (bending) of the tread at the leading and trailing edges, and also in the tyre shoulder region
- The above deflection (flattening) due to the loading will cause the tyre sidewalls to "bulb out" from their unloaded uniform shape
- The flattening mentioned above may be reduced if the pavement under the contact patch is not totally stiff but has some flexibility. Some of the deformation in the tyre will then instead take place in the pavement
- Depending on the contact pressure, tread rubber elements will be compressed and expanded when the element is released from its loaded state
- Depending on the contact pressure and the texture of the road surface in the contact patch penetrating into the tread, tread rubber will be compressed and expanded
- During driving, the static load will have a modulating component due to the road and/or tyre unevenness (or tyre unbalance) which will cause the tyre to "bounce" up and down, causing more or less flattening on the contact patch (contact area changes) and corresponding tyre deflection from the shape at the stationary load. Part of the energy due to this movement will be consumed in the shock absorber
- Tread elements will be deflected in the horizontal and lateral directions due to stick-slip actions in the tyre/road interface. Another term often used is "microslippage"
- When the tyre is driving or braking, the stick-slip forces become higher and there will be a net slip between tyre and road to transfer the driving or braking forces (shearing)
- Caused by stick-slip motions, mainly the slip, tyre rubber particles may be worn off the tyre; in which case it is not so much a deflection that causes the energy loss but the braking of molecular bonds.

- The breaking-up of molecular bonds may cause another type of deflection, namely at the trailing edge of the contact patch, the adhesion between the tyre rubber and the road surface will need a certain (very small but probably not negligible) force to break the molecular bonds, and thus there will be a small deflection due to the “stick-snap” action.

- If the tyre is subject to side forces, such as when turning or driving in a curve, or under misalignment, there will be deflections to take up the side forces along the contact patch and in the tyre areas close to the contact patch.

- If the tyre is running in water or snow, not only will gravitational energy be needed to displace the water or the snow from the tyre track, or to compress (or even melt) the snow, or to throw off the water from the tyre tread, but the forces needed to do so will create extra deflections in the tyre.

These different types of deflection will affect tyre structure, tyre tread and various parts of the tyre rubber in different ways. It is known that most of the energy losses occur in the shoulder regions of the tyre where all the mentioned deflections occur, as opposed to some other parts of the tyre where perhaps only one or a few types of deflection occur. The shoulders also are thicker and contain more rubber than other parts of the tyre, which means that there is more mass to deflect.

As should be obvious from the list above, the tyre deflections and the resulting energy losses are extremely complicated. The same applies to sound generation, where the same deflections are active, although sound generation also have substantial aerodynamic components and thus are even more complex [Sandberg & Ejsmont, 2002].

### 3.4.3 Pavement-influencing tyre losses

As stressed above, rolling resistance is a result of an interaction between tyre and pavement, and it is really difficult to distinguish between effects in the tyre and in the pavement. Some losses in the tyres are very much affected by pavement properties, and therefore are listed separately here. At least three effects are of interest:

- Road unevenness will cause the tyre to be moved up and down and the corresponding forces will create a change in the tyre deflections.

- Road texture will create local deflections and shearing of the tread in the contact area, which results in forces; mainly but not only in the vertical direction.

- Deflection of the pavement under the tyre load is not negligible, at least not for bituminous pavements. When the pavement is deflected, the tyre deflection is smaller than if the pavement were perfectly stiff. More pavement deflection means less tyre deflection which reduces tyre losses.

- Microtexture of the road surface will affect the stick-slip and stick-snap motions mentioned above, and also the rubber particle loss (may be either a positive or a negative influence). According to [Wong, 1993] 2-10 % of the rolling resistance is caused by friction between the tyre and the road, thus the effect is not negligible.

- Ruts in the pavement will create side forces increasing the tyre losses.
Fig. 3.3: Illustration of the rolling resistance generation mechanisms which are due to tyre deflections. From [Sandberg & Ejsmont, 2002].
3.4.4 Energy losses in pavements

Rolling resistance losses may occur not only in the tyre but also in the pavement. At least three effects are of interest here:

- The aggregate (stones) in the road surface may move a little under the tangential (stick-slip) forces of the tyre; especially when the tyre is driven or braked
- The pavement may deflect somewhat under the tyre load. This is a documented effect for non-paved and paved roads with weak base-course [Jamieson & Cenek, 2002] and may be important also for some asphalt roads under certain conditions
- Provided there are energy losses in the pavement, the pavement deflection will contain a component which is stronger in front of the tyre than behind it, leading to a "wave" travelling in the pavement in front of the contact patch
- Not only will the tyre lose some material; under some circumstances also the road surface will lose particles, and sometimes there might even be cracking; also these events require energy

In the three first cases, hysteresis effects are present which mean that a deformation or deflection is not fully recovered and thus some of the energy will be converted to heat. An illustration of the hysteresis curves for three different pavement types appear later in this report.

3.4.5 Bearings

In principle, there is always some friction in bearings, even in ball bearings. However, wheel bearings in good condition should have negligible RR, but one cannot exclude the possibility of some influence, which is the reason why bearing losses are included in the so-called parasitic losses mentioned in 3.4.1.

3.4.6 Tyre rotation aerodynamic losses

The rotation of the tyre and its rim will inevitably pull some air with it, which causes friction in the air and thus causes aerodynamic losses. The tread pattern will have an influence of this, as it may more or less "grab" and pull air around. At normal speeds and with reasonably well designed rims this aerodynamic contribution should be small.

3.4.7 Tyre aerodynamic drag

When tyres roll on roads they have to displace some air. This causes aerodynamic drag on the tyres, which depends on the dimensions of the tyre. The most important parameter is the "projected frontal area" (cross-section area) perpendicular to the direction of rolling, but there is also a shape coefficient $C_D$. The frontal area is usually around 2 m$^2$ for cars and 9.5 m$^2$ for trucks. For two car tyres 225/55R16, the frontal area (below car underbody) is approx. 0.13 m$^2$ which is 5-10 % of the total car frontal area, but as probably the $C_D$ is higher for a modern tyre than for a modern car, one should consider the tyre air drag as something in the order of 10 % of the total car air drag. Comparing the frontal area of tyres having a load index of 95, the area of a 275/35R18 (extreme low profile wide tyre) is 30 % higher than that of a tyre 205/75R14, mentioned as an example. It means that tyre air drag cannot be neglected; not even the difference in air drag between tyres for the same load.

---

2 No data about shape coefficient for tyres have been found by the editor
3.4.8 Suspension

An unavoidable effect of the road surface is the vertical or near vertical vibrations of the tyre/wheel/suspension assembly caused by road unevenness. The energy losses from this may to some extent occur due to extra deflections in the tyre, but more so as energy conversion (to heat) in the shock absorbers. With certain measurement methods it is difficult to separate the shock absorber losses from the rolling resistance losses and some might argue that it is practical and justified to include shock absorber losses into rolling resistance as it is caused by the tyre movement during rolling on an uneven road.

3.5 Problems with the present rolling resistance concept and measure

The rolling resistance coefficient (RRC) was first developed to present a characterization of the rolling resistance of tyres because there is a near-linear relationship between rolling resistance and load, and the coefficient allows comparison across different tyres. However, an American study found that the way rolling resistance is normalized to RRC (force to keep the tyre rolling divided by the vertical load) was not consistent over a large range of tyre sizes and loads [Evans et al, 2009]. RRC tends to be relatively lower for larger tyre diameters than for small tyres, despite the fact that larger tyres are likely to consume more fuel. Given that rolling resistance is considered as an indicator of fuel economy, this problem will be particularly important when RRC is used in a rating system to categorize a wide range of tyres. Therefore, Evans et al argue that using the force instead of the coefficient might be better; in which case load will be a more important test parameter to control.

Given that it may not always be possible to use the same load when testing RR, and that the major reasons for tyres with larger diameters having lower RRC than smaller tyres are large differences in tyre inflation and internal construction, the authors of this report prefer to use the RRC as the crucial parameter when comparing tyres and pavements.

Another problem related to the current conception of rolling resistance, at least in standards, is the lack of a pavement perspective. One of the goals of the MIRIAM project is to correct that problem.

3.6 Discussion regarding measured contributions to energy losses and resistances with the methods employed in MIRIAM

In the MIRIAM project, the following RR measurement methods will be used:

- The drum method (both for light and heavy vehicle tyres)
- The coastdown method (both for light and heavy vehicle tyres)
- The trailer method (mainly for light tyres, to a lesser extent also for heavy tyres)
- Possibly, also a fuel consumption method may be used, utilizing a complete vehicle

These are described in a later chapter in this report. The drum method will be used for special studies, but not much to determine the relation between RRC and pavement characteristics, as it is a laboratory method where it is impractical to put many different pavements on the drum. The coastdown method will be used on a number of roads and for both light and heavy vehicles. The trailer method is the one that will be used most of all.

The three first methods measure (pick-up) the various energy losses or rolling resistances according to Table 3.1.

Ideally, the coastdown method gives the most comprehensive data sets, relating to both light and heavy vehicles and their tyres. This data is needed in order to establish a good model for calculating the effect of pavement characteristics on energy consumption in road vehicles. However, to employ the coastdown method on a really large scale is not possible within reasonable budget limits. It is hoped that by using both the coastdown and the trailer
methods on a selection of pavements, it will be possible to measure all contributions to energy losses for a rolling vehicle on a limited selection of pavements (coastdown) and for a rolling tyre on a large number of pavements. By comparing the results, and creating some model based on them, it may be possible to distinguish between various important contributions. However, it must be realised that using the trailer method for heavy vehicles is impractical and will be possible only to a very limited extent.

These methodology issues are treated in much more detail in a following chapter, and are mentioned here only because they affect the data collection and the measures to use.

Table 3.1: Various loss/resistance contributions picked-up for a rolling test object by the three methods to be employed in MIRIAM.

<table>
<thead>
<tr>
<th>Method</th>
<th>Contributions picked-up by the method</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum (laboratory facility)</td>
<td>• Tyre losses (due to the tyre/road interaction)</td>
<td>Parasitic losses are eliminated Pavement losses may be measured only if realistic pavements are fitted on drum</td>
</tr>
<tr>
<td>Coastdown (full vehicle)</td>
<td>• Tyre losses (due to the tyre/road interaction) • Pavement losses (in the pavement itself) • Bearing frictional losses • Tyre rotational aerodynamic resistance • Tyre air drag (when moving through the air) • Suspension losses • Transmission losses (some) • Air drag (full vehicle incl tyres)</td>
<td>This method measures all contributions when the test vehicle is rolling, from a higher to a lower speed Air drag is eliminated by special calculations The main problem is to isolate the parts</td>
</tr>
<tr>
<td>Trailer</td>
<td>• Tyre losses (due to the tyre/road interaction) • Pavement losses (in the pavement itself) • Bearing frictional losses • Tyre rotational aerodynamic resistance • Suspension losses</td>
<td>Tyre air drag is not measured provided the test tyre is enclosed Some suspension losses may occur, but will maybe not be typical ones, depending on type of suspension used in the trailer</td>
</tr>
</tbody>
</table>

3.7 Suggested terminology and definitions
Based on the discussions earlier in this chapter; including practical measurement concerns, it is suggested to use the following terminology structure and distinction between resistances at various levels in the vehicle driving system:
Level 1: (Vehicle) Driving resistance (DR)
includes:
  • (Vehicle) Propulsion resistance (PR)
  • (Vehicle) Aerodynamic resistance (air drag) (AR)
  • Vehicle rolling resistance (RRv)

Level 2: (Vehicle) Propulsion resistance (PR)
includes:
  • Inertial resistance (IR)
  • Gravitational resistance (GR)
  • Engine resistance (ER)
  • Auxiliary equipment resistance (AER)

Level 2: (Vehicle) Aerodynamic resistance (air drag) (AR)
includes:
  • Body air resistance (body air drag) (ARb)
  • Tyre air resistance (tyre air drag) (ART)

Level 2: Vehicle rolling resistance (RRv)
includes:
  • Tyre/road rolling resistance (RRt)
  • Bearing resistance (BR)
  • Suspension resistance (SR)
  • Transmission resistance (incl parts rotating with the tyres) (TR)

Level 3: Tyre/road rolling resistance (RRt)
includes:
  • Tyre deflection (hysteresis) losses (due to the tyre/road interaction)
  • Tyre driving force resistance (extra losses when tyres are driven or braked)
  • Tyre side force resistance (extra losses when tyres are subject to sideway forces)
  • Pavement deflection (hysteresis) losses (in the pavement itself)
  • Tyre rotational aerodynamic resistance

Consistent with the structure above, Level 3 also includes the following components, which
need not be further layered for the purposes of this report:

Level 3: Bearing resistance (BR)
Level 3: Suspension resistance (SR)
Level 3: Transmission resistance (incl parts rotating with the tyres) (TR)

Fig. 3.4 illustrates this terminology structure, although the level 4 items have been neglected
there.

It should be noted that the transmission resistance include two distinctive parts, not shown
above but which may have different influences depending on whether the vehicle is coasting
or driving, namely churning and mechanical losses. If the vehicle is coasting, the mechanical
losses should be at a minimum as there is no power transfer, but both at coasting and driving
there will be churning losses.
Fig. 3.4: Illustration of the suggested terminology structure (only the upper 3 levels).

The placing of some of the items above may need justifications:

**Body and tyre air resistances:** Why make a distinction between these? The reason is that these two depend on separate selections of vehicle body and tyres for the vehicle. When the vehicle is in new condition, the body and the tyres are of course one unit, as designed and selected by the vehicle manufacturer, but when tyres need to be exchanged the selection may be totally independent, possibly resulting in a change in the total air drag due to the new tyres.

**Bearing resistance:** Why is this not part of rolling resistance? The bearing of course influences how easy the tyre will roll, but it must be treated as a separate item as it is a component which is totally different from the tyre.

**Tyre rotational aerodynamic resistance:** Why is this placed under rolling resistance and not aerodynamic resistance? The reason is that this phenomenon is a tyre property, as determined by the design of tyre and especially its tread. It is also difficult to measure it distinctively from rolling resistance.

It may be argued that there might also be a component of air resistance due to turbulence in the rotating rim area. This effect is neglected here. If desired, that effect should be placed under "Vehicle rolling resistance", since it affects the rolling but it is not a tyre component.

With the structure and terminology listed above, the three methods will measure parameters according to Table 3.2.

Depending on trailer construction, and test wheel alignment, some trailers may, without intention, measure some side forces. They will also be more or less sensitive to inertial or gravitational forces, depending on trailer and measurement system configurations. It will be important to keep these effects low, as well as to avoid the effects of bearing and trailer
suspension losses on the measured values, in order that the trailers will measure pure 
tyre/road rolling resistance. Another option may be to create and use a model for the 
contribution of various effects and by measuring all relevant parameters separate the effects 
for each measured case.

Table 3.2: What the three methods to be employed in MIRIAM will measure.

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameters measured</th>
<th>Parameters/losses not measured</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drum</strong></td>
<td>• Tyre/road rolling resistance</td>
<td>Pavement deflection</td>
</tr>
<tr>
<td>(laboratory</td>
<td>+ &quot;parasitic losses&quot; (incl bearing</td>
<td>Driving force resistance</td>
</tr>
<tr>
<td>facility)</td>
<td>resistance) which will be corrected for</td>
<td>Side force resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Losses on a plane surface</td>
</tr>
<tr>
<td><strong>Coastdown</strong></td>
<td>• Vehicle rolling resistance</td>
<td>Data processing allows separation of aerodynamic resistance and</td>
</tr>
<tr>
<td>(full vehicle)</td>
<td>• Vehicle aerodynamic resistance</td>
<td>vehicle rolling resistance; to some extent also identifying some</td>
</tr>
<tr>
<td></td>
<td>In principle, &quot;everything&quot; at coasting is</td>
<td>components of RRv.</td>
</tr>
<tr>
<td></td>
<td>measured; the problem is to separate</td>
<td>Mechanical transmission resistance (depending on driving torque)</td>
</tr>
<tr>
<td></td>
<td>out the effects in the data processing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>stage</td>
<td></td>
</tr>
<tr>
<td><strong>Trailer</strong></td>
<td>• Tyre/road rolling resistance</td>
<td>Driving force resistance</td>
</tr>
<tr>
<td></td>
<td>• Bearing resistance</td>
<td>Side force resistance</td>
</tr>
<tr>
<td></td>
<td>• (Trailer) suspension losses</td>
<td>Transmission resistance</td>
</tr>
</tbody>
</table>

The same applies to the drum method; the so called parasitic losses must be controlled (as 
ISO 28580 does). If one wants to receive as comparable values from drum and trailer 
methods as possible, one should treat bearing resistance, rim air resistance and tyre rotation 
air resistances in the same way, which requires breaking-up of the "parasitic losses".

The coastdown method will never be able to measure a "pure" tyre/road rolling resistance (as 
is the case also for the other methods). It will also be difficult to calculate the tyre/road rolling 
resistance, since it would require separating out the bearing resistance, suspension 
resistance and the two types of transmission resistance, which is very difficult. One possibility 
would be if the latter may be neglected, or estimated, in comparison to the tyre/road rolling 
resistance, an issue which should be studied in MIRIAM, by comparing vehicle and tyre/road 
rolling resistance.

It is concluded that the three methods will not measure identical things, but by using all three 
with different purposes, and by comparing results, it will be easier to model the energy 
consumption of full vehicles as influenced by choice of tyres and as influenced by various 
pavement properties.
4 VARIABLES AND PARAMETERS AFFECTING ROLLING RESISTANCE

4.1 Tyre properties

4.1.1 Tyre internal properties

The internal structure of tyres consists of a carcass made of steel ("steel radial tyres") or textile wires, an inner lining made of some rubber compound, a belt made of metal with some extra reinforcing layers for the larger tyres, and an "undertread" made of rubber compound. Outside of the "undertread", there is the tread which is intended to provide the road contact and thus be the "wearing part", made of some rubber compound and having a pattern; mainly for drainage purposes. This outer part of the tread can be renewed (retreaded). The outside of the sidewalls is made of rubber too, but it is usually another type of compound than the tread rubber. The transition between tread and sidewall is called shoulder, and in this region there is extra thick rubber, where much of the energy is consumed. The part of the tyre that sits on the sidewalls is usually called the "crown".

The belt is made in a way that makes it incompressible and unstretchable. In the leading and trailing parts of the contact patch there is the maximum bending of the tyre crown. Since the belt is stiff it means that the rubber under the belt (inner lining) will be compressed and the rubber above the belt (the tread) will be expanded when a particular part of the crown passes through the leading and trailing edges during the tyre rotation. This compression and expansion of the rubber in the two layers around the belt will create hysteresis losses in the rubber, i.e. the energy is converted to heat.

It follows that the part of the inner structure that consumes energy is mainly the rubber and not the belt or carcass. To use low-hysteresis rubber is, therefore, crucial for low RR.

However, this is not to say that the carcass and the belt have no influence of RR. They will have an indirect influence, since the construction determined partly by these tyre components will affect, for example, the shape of the contact patch, which has an influence on stick-slip motions.

The authors have not found quantitative data on how the internal structure affects the rolling resistance. This is usually a matter of development and testing within the tyre industry and such information is rarely released outside the company doors.

4.1.2 Tyre external properties (dimensions)

Tyre dimensions have a substantial influence on rolling resistance. An interesting statistical multivariate analysis of which factors that seem to influence the measured RRC, based on 170 tyres, is presented in [TRB 286, 2006]. Table 4.1, copied from the TRB report, shows the main results. Here, the most interesting variable to look at is the t value since it shows how statistically significant the relation was found to be; the higher value the more significant was the parameter.

In this analysis, the following parameters came out as especially influential:

- Rim diameter (which is highly correlated with tyre outer diameter), with t = 9.3
- Aspect ratio (quotient of tyre height/tyre width), with t = 6.3
- High speed rating (speed categories W, Y, Z), with t = 5.4
- Tread depth, with t = 4.9.

Of these, the two most important ones are dimensional effects. It is reported that increasing rim diameter by 1 inch, or about 6.3 percent for the average tyre in the data set, reduces RRC by 5 to 8 % [TRB 286, 2006]. Since outer tyre diameter is approximately 65 % higher
than the rim diameter (an estimate from tyre data manuals), 6.3 % increase in rim diameter corresponds to roughly 4 % of outer tyre diameter increase.

Table 4.1: Result of a multiple regression analysis of RRC data for a set of 170 tyres tested in the USA, intended to study the effect of various tyre parameters (left column) on the RRC, with statistical significance shown in column “t”. From [TRB 286, 2006].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>t</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>hispeed</td>
<td>.160</td>
<td>.030</td>
<td>5.4</td>
<td>.102</td>
<td>.221</td>
</tr>
<tr>
<td>midspeed</td>
<td>.047</td>
<td>.020</td>
<td>2.3</td>
<td>.007</td>
<td>.098</td>
</tr>
<tr>
<td>michelin</td>
<td>-.064</td>
<td>.020</td>
<td>-.32</td>
<td>-.104</td>
<td>-.025</td>
</tr>
<tr>
<td>rimdiameter</td>
<td>-.066</td>
<td>.007</td>
<td>-9.3</td>
<td>-.081</td>
<td>-.053</td>
</tr>
<tr>
<td>aspectratio</td>
<td>-.009</td>
<td>.002</td>
<td>-6.3</td>
<td>-.012</td>
<td>-.006</td>
</tr>
<tr>
<td>treaddepth</td>
<td>.042</td>
<td>.009</td>
<td>4.9</td>
<td>.025</td>
<td>.060</td>
</tr>
<tr>
<td>tractionB</td>
<td>-.120</td>
<td>.036</td>
<td>-3.3</td>
<td>-.192</td>
<td>-.048</td>
</tr>
<tr>
<td>ecosdummy</td>
<td>-.044</td>
<td>.024</td>
<td>-1.8</td>
<td>-.094</td>
<td>.005</td>
</tr>
</tbody>
</table>

Note: Number of observations = 170; $R^2 = .52$; adjusted $R^2 = .50$.

Another example is shown in Fig. 4.1 which is from [Aimon, 2005]. Using the blue regression curve there, starting from diameter 650 mm, which gives an RRC of 0.010, if increasing diameter by 4 % (as in the TRB example above) to 676 mm, RRC is reduced to approx. 0.0096, which is a 4 % reduction. This is evidently a little lower than the TRB report found.

Fig. 4.1: Relation between tyre diameter and RRC (RRC expressed in kg/ton) for two speed classes (tyre speed categories S, T and H in blue and V and Z in red). From [Aimon, 2005].
In [Michelin, 2003] it is stated that 10 mm of increase in rim diameter reduces RRC by 1 %, and that 10 mm of increase in tyre sidewall height reduces RRC by 1 %. For an average tyre outer diameter of 650 mm, 10 mm increase corresponds to 1.5 %. If 1.5 % causes an RRC reduction of 1 %, then 4 % diameter increase should cause an RRC reduction of 2.7 %.

Thus, the estimates reported above range from 2.7 % to 8 % of RRC reduction for a diameter increase of 4 %. This is a wide range which suggests that further research is needed.

In the ECRPD project the influence of tyre dimension is estimated with the equation:

\[ \text{RRC} = k \cdot \text{OD}^{1/3} \]

where OD = tyre outer diameter. For example, if OD is increased by 4 % (as in the example by TRB above), RRC will decrease by 1.3 %, which seems to be only half of the lowest estimate above, which thus may need an adjustment.

4.1.3 Tyre speed category

In the TRB report mentioned above high speed category tyres came out of the multivariate analysis as having higher RRC [TRB 286, 2006]. Compared with tyres with lower speed ratings (S, T), tyres with the highest speed ratings (W, Y, Z) were found to have 10 to 22 % higher RRC, while tyres with middle speed ratings (H, V) had 1 to 9 % higher RRC.

The data from Fig. 1 also shows the influence of speed category. The higher ones (V and Z) give approx. 10 % higher RRC than the lower ones (S, T and H). This is a little higher than in the TRB report.

4.1.4 Tyre rubber compound and rubber hardness

It is widely recognized that the substantial improvements in rolling resistance achieved in the last two decades have been largely made due to the use of better rubber compounds. For example, the addition of silica has been favourable.

A study in Germany reported RRC reductions between 5 and 24 % when replacing carbon black with silica in car tyres, for three different brands in two tyre sizes [Glaeser, 2005].

A study at TUG using two tyres of the same brand, type and dimension but with rubber of two different stiffnesses showed approx. 8 % of RRC reduction for a Shore A hardness reduction from 71 to 62, as shown in Fig. 4.2.

![Influence of tread rubber hardness on the rolling resistance coefficient (RRC)](chart)

Fig. 4.2: Difference in RRC between two tyres identical in all respects except tread rubber compound and hardness. Unpublished data from TUG.

3 See Chapter 6 for a description of the ECRPD project
4.1.5 Tyre condition

During a lifecycle a tyre undergoes degradations due to mechanical wear and chemical ageing which affect not only durability and safety but also tyre/road noise emission and rolling resistance. Therefore, any calculation involving long-term rolling resistance change needs to specify the conditions under which the coefficient is tested; among these the tread depth.

One of the results of the multi-regression analysis presented in the TRB report [TRB 286, 2006] was that tread depth affects RRC. It was found that a tread depth decrease of around 9% gave an RRC reduction of around 4.3%. This was for car tyres.

A few years ago, VTI, TUG and BASt made a study with the purpose to study how much tyre/road noise and rolling resistance change when car tyres are worn down from the original 8 mm tread depth to 2 mm, and when chemical ageing of the tyre rubber is simulated by exposure to heat. Six car tyres of different types were selected for the study, which were worn on a wear machine in steps of 2 mm tread depth. Before, between and after these wear sessions tyre/road noise and rolling resistance were measured on two drum facilities with different surface textures, including replicas of ISO surfaces.

The results showed that tyre wear and tread depth were found to have a dramatic effect on rolling resistance. When tyre treads are worn from new condition (8 mm) to 2 mm tread depth, the rolling resistance may decrease by about 20%. The RRC changes (Cr on the ordinate axis) from new to worn out condition (8 vs 2 mm tread depth) are shown in Fig. 4.3.

![Fig. 4.3: Results of the rolling resistance measurements on a plain steel 5.5 m drum of the BASt PFF facility, for the six tyres in new and fully worn condition. Copied from [Sandberg & Glaeser, 2008].](image)

However, the data in Fig. 4.2 are for tyres in essentially new condition, except for the tread wear. The separate study on the effect of ageing is shown in Fig. 4.4. This ageing was simulated to correspond to the chemical changes over a normal tyre's lifetime.

Probably, the above effects of tread wear and ageing would be additive. Thus, the total effects from a new unworn to an old wornout tyre would be up to 30%. Although this is a large affect, it does not seem to be as large as the one reported in [TRB 286, 2006].

Note that these data are only for car tyres. Truck tyres have approx. twice as thick treads as car tyres. For heavy truck tyres of typical sizes (22.5"), it has been reported that around 30% of rolling resistance comes from the tread, according to measurements on a drum made by Nokian Tyres in Finland. Thus, if the tyre is totally worn the RR is 30% lower [Siltanen, 2010].
Fig. 4.4: Results of RR measurements on a drum with smooth-textured Safety Walk (blue left) and a drum with rough-textured surface dressing (red right), for the five tyres that were aged artificially from the new condition. The vertical scale (RR coefficient in \%) shows the difference from new to aged condition, which means that negative values are the results of reduced RR when tyres have aged. Copied from [Sandberg & Glaeser, 2008].

4.1.6 Tyre rolling speed

According to [Duleep, 2005], RRC speed dependence is small at speeds < 60mph (approx 97 km/h). However, beyond the so-called critical speed (usually over 80 mph, approx 130 km/h) standing waves develop and the RRC increases rapidly.

Tests in a VTI-TUG project including approx 100 car tyres, tested on the TUG drum facility, having two very different drum surfaces, showed very small speed influence on the RRC for the average tyre; see Fig. 4.5. The RRC increase from 80 to 120 km/h is only approx. 2 

In a PhD thesis the speed influence was rather closely studied and a truck tyre RR model finally showed a speed influence between 50 and 100 km/h of max. 2 \% [Sandberg, 2001].

Contrary to the examples mentioned, Descornet in the 1980's noted a moderate increase of RRC with speed [Descornet, 1990]. However, this is explained by his trailer being exposed to air drag; thus it is an air drag effect on the tyre in his special set-up, where the test tyre is partly "protected" by the towing van and a fender, but there is nevertheless significant air drag in the wake behind.

Fig. 4.5: RRC versus speed, tested for approx. 100 car tyres of various brands and dimensions. Unpublished data from TUG/VTI.
4.1.7 Tyre load and inflation pressure

According to [Duleep, 2005], "RR varies linearly with load and inversely with square root of inflation pressure. There is an interactive effect where RR is less sensitive to inflation pressure at lighter load." He probably meant RR expressed as a horizontal force, since when RRC is normalized with respect to vertical load, there is usually no effect of load.

Unpublished data from BRRC suggests that the load influence on RR is a little higher than directly proportional 1:1 to load [Bergiers, 2011].

According to [Michelin, 2003] the inflation pressure influence is not as dramatic as Duleep suggests, although the shape of the relation is similar.

Regarding inflation pressure [Bergiers, 2011] also suggests a less dramatic relation than Duleep; see Fig. 4.6.

A study about the effect of tyre inflation pressure on fuel consumption of a car is presented in [Jonsson, 2007]. Jonsson concluded that fuel consumption decreased by 2.7 % as inflation was increased from 15 % below recommended tyre inflation up to the recommended one.

![Fig. 4.6: RR versus travelled distance for a tyre inflated with five different inflation pressures. Unpublished data from [Bergiers, 2011].](image)

4.1.8 Tyre slip angle

The alignment of the test tyre is very important for rolling resistance; only a small slip angle difference from the ideal 0° can make a big difference in RRC. Fig. 4.7 illustrates this. As little as half a degree may change RRC by a non-negligible amount.

![Fig. 4.7: RRC versus slip angle; according to diagram in [Duleep, 2005] (its origin is unknown).](image)
4.2 Road properties

4.2.1 Texture and unevenness – old data

Some groundbreaking work on rolling resistance and fuel consumption related to road surface properties were made in the 1980's. Using a special RR trailer, as well as a profilometer for the texture range and another one for the unevenness range, Descornet at BRRC analysed the relation between RRC and unevenness, megatexture and macrotexture. He found that the most sensitive range was the megatexture range [Descornet, 1990]. See Fig. 4.8. A little earlier, Sandberg at VTI, made corresponding measurements and analyses, but the big difference was that he measured fuel consumption with a full Volvo 240 car and not rolling resistance; see results in Fig. 4.9 [Sandberg, 1990].

![Fig. 4.8: Correlation between RRC and road roughness/texture level as a function of texture wavelength](image)

![Fig. 4.9: Correlation between fuel consumption per km and road roughness/texture level as a function of texture wavelength](image)
These two diagrams look quite differently. However, in a way, the difference is logical, since when making fuel consumption measurements, in contrast to trailer measurements, the suspension losses are present and they should peak in the area where Sandberg's data peak. It may be noticed that in the megatexture and macrotexture areas Descornet's and Sandberg's data are not very different.

By fuel consumption measurements using a passenger car on roads representative of the French network and by assessment of heat emission related to the conversion of mechanical energy in dampers during tests on a vibration bench, a French study showed an "overconsumption" of fuel of up to 6 % for a car which had an average fuel consumption of 7 litres/10 km [Laganier & Lucas, 1990]. The results are illustrated in Figure 4.10. The left part shows results of fuel consumption measurements with a car on various unevenness levels on French roads (note that it is not an IRI scale). The right part shows results of measurements and calculations of power lost in shock absorbers (dampers) as a function of roughness level, for three wavelength ranges, namely small (1 m < \( \lambda \) < 33 mm), medium (3.3 m < \( \lambda \) < 13 m) and longer than 13 m road roughness wavelengths (\( \lambda \)). Note that the "small" wavelength range (1 m < \( \lambda \) < 33 mm), which includes the entire megatexture range and the end ranges of unevenness and macrotexture, was by far the most important one, even for suspension losses. That is indeed a unique finding, which is important for MIRIAM.

Fig. 4.10: Extra fuel/energy consumption according to road roughness level. See text for explanations. From [Laganier & Lucas, 1990].

The value of these data is that they suggest that one shall measure both the tyre rolling resistance and the suspension losses, and that the megatexture range is very important for tyre RR. So far, in the newer studies, megatexture has been neglected; albeit VTI and some others regularly measure it.

In an attempt to collect all known data on the relation between rolling resistance and road surface properties, [Sandberg, 1997] arrived at the following conclusion based on a table summarizing 15 studies:

"From the table it can be concluded (tentatively) that the average influence is 10 % for macrotexture, 12 % for megatexture, and 8 % for unevenness. These values represent the influence on fuel consumption when comparing the smoothest road surfaces with the roughest on the normal public road network (in industrialized countries). Within the same type of road, but in different "normal" conditions or with different "normal" pavements for that type of road considered, it is more realistic to use approximately half of the values in the table as representative of potential influences."
4.2.2 Texture and unevenness – new data

On behalf of VTI, TUG has measured RRC on a number of road surfaces in Sweden and Denmark in the past 5 years using the TUG "R² trailer". A compilation of such RRC data, plotted as a function of Mean Profile Depth (MPD), the latter measured according to ISO 13473-1, appears in Fig. 4.11.

These are clustered according to the data collection campaign in which the data were collected, and a regression line is plotted through each such set of data. The fact that the regression lines do not coincide probably reflects one or both of the following possibilities:

- The temperatures during the measurements differed. When correcting for temperature as described above but not shown in the figure, the lines get closer to each other, but they do not coincide.
- There is, or at least was in the earliest years, some uncontrolled calibration error giving a certain bias in some data sets.

However, it is apparent that the slopes of the lines are amazingly consistent. The slope indicates the sensitivity of RRC to a change in MPD, and these data seem to be reliable. The regression line constants which are plotted in the diagram show that the slope varies between 0.0016 and 0.0020.

![Fig. 4.11: Results of Swedish-Polish studies of the relation between RRC and macrotexture, for car tyres, where macrotexture is represented by the MPD. A certain cluster of points and associated regression line belong to the same data set, measured within a few days, whereas the data sets have been collected in 2009-2010.](image)

An important issue is whether the effect of MPD on RR depends on the speed. VTI-TUG measurements at 80, 100 and 120 km/h on the TUG drum facility (with sandpaper and a...
rough-textured surface dressing), indicated the following relation between RRC, the road surface parameter MPD and speed (based on RRC of approx 100 car tyres):

$$RRC = 0.01065 + 0.002012\cdot MPD + 0.0000064\cdot MPD\cdot (V-20)$$

where MPD is in mm and V (speed) in m/s.

The combined term MPD (V-20) has a very small coefficient, which is not significantly different from zero for the data available. RRC versus speed data indicates that RRC slightly depends on the speed. However, this dependence does not necessarily have to be coupled to MPD. A conclusion from this is that the MPD effect is either independent of the speed or depends very weakly on it.

Measurements by VTI in the ECRPD project (see Chapter 6) and national projects using the coastdown method have indicated the following (most recent) relation between RRC and the road surface parameters MPD and IRI:

For a car:

$$RRC = 0.0148 + 0.0020\cdot MPD + 0.00064\cdot IRI + 0.00005\cdot IRI\cdot (V-20)$$

For a truck:

$$RRC = 0.0061 + 0.0014\cdot MPD + 0.00095\cdot IRI + 0.000076\cdot IRI\cdot (V-20)$$

where V denotes the speed [m/s] and IRI is in [mm/m]. Note that the constant coefficient here includes also the transmission resistance. This should be subtracted from the constant term to yield the true RR.

The measurements for the car were done using a Volvo 940 and two types of tyres (summer and winter tyres). Truck measurements were performed with a Volvo FH-480 with a total weight of 27 tons. The coefficients have been adjusted to temperature 0 °C since these measurements were made at rather low temperatures.

It appears that the IRI is much more important for a truck than for a car while the contrary is true for MPD. Note also that the influence of IRI on the RRC is clearly dependent of the velocity.

It is interesting to see that both these totally different methods show the RRC vs MPD relation to have a slope of 0.020 (for car tyres) which is within the narrow range obtained with the trailer measurements.

It is important to note that these results are (reasonably) valid for the test vehicles (a Volvo 940 and a Volvo FH-480 truck) and the tyres used, but it is not known how representative they are for the vehicle park as a whole.

The data above are by no means the "final" relations. They should be regarded as results of pilot tests. One task of MIRIAM SP 1 will be to collect much more data in order that the equations may be made much more accurate and more generally valid.

4.2.3 Microtexture

Microtexture is the type of road roughness that affects skid resistance, and thus the so-called microslippage (stick-slip) effect.

A laboratory drum investigation by [de Raad, 1978] showed that 10 tyres had an average of as much as 5 % more rolling resistance on a sandpaper-like surface than on a smooth steel surface. This is more likely to be a microtexture rather than a macrotexture effect.

There are no other data known to the authors that shows whether this is an important effect or not. However, it is logical that it is so, since the microslippage effect is absolutely a significant effect of rolling resistance.
4.2.4 Stiffness and internal pavement losses

As mentioned in an earlier section, the bow-wave in the pavement substructure in front of a rolling tyre, as well as the deflection of the pavement under a loaded tyre, should result in some energy consumption which should be reflected in a contribution to rolling resistance. The reason is that deflections in the pavement should be subject to hysteresis losses; as illustrated in Fig. 4.12. The area within a loop is equal to the hysteresis losses, which means that the asphalt pavement has much higher losses of this type than the cement concrete pavement (2.2 versus 0.43 Nm) [Lenngren, 2009]. The energy loss determined from a FWD test is not directly comparable with rolling resistance. The real rolling resistance is believed to be approximately 70 – 80 % of the maximum energy loss determined by the FWD test [Schmidt et al, 2009].

The cement concrete industries, especially in North America, have claimed that their pavements give less RR than bituminous pavements, since a long time ago, but most if not all studies investigating this have missed to control factors such as IRI, macrotexture and microtexture, or simply do not report any details of this, and some studies have been sponsored by the industry. Therefore, the reduced RR might be explained by other factors than the stiffness [Boujard, 2009].

A laboratory study at TRL, which controlled the surface properties very well, indicated a positive effect of stiffness; however, the effect was not statistically significant [Benbow et al, 2007]. Two studies by VTI, comparing a cement concrete pavement with an SMA pavement found that the positive difference in favour of the concrete pavement could be explained by the different macrotextures [Jonsson & Hultqvist, 2009][Sandberg, 2010].

![Figure 4.12: Illustration of the hysteresis effect measured with a Falling Weight Deflectometer (FWD) on a cement concrete pavement (left part), compared to an asphalt concrete pavement (right part). Figure processed by the editor from [Lenngren, 2009].](image-url)
In addition, a Danish theoretical study concluded that the part of the rolling resistance influenced by the deformation in the pavement seems to be very limited and therefore the effect on energy consumption which can be obtained by using stiffer pavements is also very limited. The test showed that even if the contribution from the deformation on rolling resistance was completely eliminated, the maximum reduction on the complete rolling resistance would be less than 4% for trucks and a significantly lesser contribution when looking at passenger cars [Schmidt et al, 2009].

A study in New Zealand [Cenek et al, 1996], has pioneered in trying to quantify such potential effects. Their results showed that fuel consumption for heavy vehicles operating at maximum legal axle weights ranged 13% between the most and the least rigid pavements. In a later multiple-regression analysis they found the pavement rebound deflection to be the most significant factor when testing with a number of medium-weight trucks; more important than road roughness [Jamieson & Cenek, 2002]. However, these softer pavements were "sealed roads": these are all-weather dust-free surfaces. Sealing is done with a wide range of technologies from bitumen seal to thin (not load bearing) asphalt surfacing. Most probably, these roads are much softer than regular asphalt concrete or SMA pavements on a bound base-course.

The overall conclusion is that pavement stiffness cannot be excluded as an important factor influencing rolling resistance, and should be included in studies in the MIRIAM project. The still open question is as to what extent and under which conditions (temperature, type of pavement and light versus heavy vehicles) when stiffness is a major factor to consider.

### 4.2.5 Road rutting, crossslope, curves and gradient

To be supplemented in future version of this report.

### 4.2.6 Road condition

There are a few reports about the effect of snow on rolling resistance [Kihlgren, 1977] [Lidström, 1979] [van Es, 1999], but they were made with aircraft tyres in mind and are a little difficult to assess for road conditions and road tyres. However, there is no doubt that the effects of snow are large. In fact, the model suggested in [Lidström, 1979] is presently implemented in VTI's VETO model, although the implementation is not easy since for an articulated truck (for example) there are many tyres, some rolling in different lateral positions, where snow conditions differ, some rolling in the same track with different snow compaction.

An effect which is mostly forgotten in studies of texture influence on fuel consumption is the tyre drag effect on surfaces partly covered with water. The water level inrut sand pools (the latter is often an effect of megatexture) will be partly influenced by the macrotexture. Non-uniform water depth may cause vehicle instability [Hight et al, 1993] but also increased fuel consumption. The water depth influences fuel consumption by at least about 10% according to [Sävenhed, 1986]. A model developed in an MSc Thesis is presently implemented in the VETO model for calculating the effect of water on the pavement [Olsson, 1984].

### 4.2.7 Survey of rolling resistance of 40 Dutch test track surfaces

In 2008 TUG was contracted to conduct measurements of RR on the various test sections of the Kloosterzande test track in southern Netherlands. This had for some years been a test field for noise measurements within the huge Dutch IPG programme. In total 40 test sections were measured, using two test tyres: the SRTT and a Continental CPC2 LI98. The latter is a conventional car tyre. The tests are reported in [Lopez, 2010] and [van Blokland et al, 2009].
There were a few problems associated with the measurements that need to be noted:

- The test sections were very short; most of them were 80 m long, a few were only 40 m long. The actually measured lengths varied between 15 and 76 m, depending on test section. This is much shorter than normal measured distances and thus gives poor uncertainties, even though many extra runs were made to compensate for it.

- The test track surfaces were never exposed to regular traffic; they were in new unworn condition.

Nevertheless, as it is a large data set, it is interesting to take a look at the results; see Fig. 4.13. In the diagram each bar represents the average RRC measured on a test section. The whiskers (lines imposed around the top of each bar) show the range between the measured maximum and minimum values.

It appears that the surface dressings which are very rough-textured have an exceptionally high RR coefficient. However, such surface dressings exist on a road only a relatively short time since they lose texture when they are exposed to traffic. Most of the rubber surfaces also have high RRC. Nos. 17 and 18 are similar to 16 except that they have a layer of rubber under the top layer, which indicates that surface stiffness has an effect, as of course also the high RRC of most other rubber surfaces suggests. Otherwise, the surfaces with low RRC are generally such with small maximum aggregate sizes or low texture. There is no consistent difference between dense and porous surfaces.

It is also worth noting that the two tyres seem to classify the test sections in a similar way. Visually, the correlation between the RRC values for the Continental tyre and the SRTT looks amazingly good, apart from a generally lower level of all RRC values, and deviations from perfect correlation may well be within uncertainty limits. As the SRTT is intended to represent car market tyres in the classification of RR properties of road surfaces this is a very satisfactory observation.

4.3 Bearing properties and condition

To be supplemented in future version of this report.

4.4 Suspension properties and condition

See also Section 4.2.1.

Apart from what is written in 4.2.1, it may be mentioned that work at the State University of New York has now succeeded in producing a shock absorber where the vibration energy is recovered and converted into electric energy [PhysOrg, 2010]. In this regenerative shock absorber, a smaller magnetic tube slides inside a larger, hollow coil tube, producing a magnetic flux. The researchers estimate that, for typical driving conditions, the system can improve fuel efficiency by 2-10 %. If this were correct, and assuming that the energy conversion would have a maximum efficiency of 50 %, the fuel consumption due to the shock absorber and the regenerative part would be 4-20 %. That would mean that the losses in the suspension would be in the same range as tyre rolling resistance losses, which is remarkable. However, the results of these efforts must be studied more to draw safe conclusions.
**Explanation of road surface types:**

- ISO 10844 ref surface
- SMA (0/6, 0/8, 0/11 and 0/16)
- DAC 0/16
- Thin layered surfaces
- PAC with different stone-sizes and layer thickness
- Two-layer PAC with different stone-sizes and layer thickness
- Eight experimental rubberized surfaces
- Two single-layer surface dressings

**Fig. 4.13:** Results of measurements of the RRC on 40 test sections at Kloosterzande test track in the Netherlands. Diagrams processed from [van Blokland et al, 2009]. The upper diagram is for the Continental tyre, the lower diagram for the SRTT.
4.5 Temperature influence

One of the factors affecting RR most of all is the ambient air temperature. This is stated in [Michelin, 2003] to be:

"The variation in rolling resistance as a function of temperature is not linear. However, between 10 and 40 °C, a variation of 1 °C corresponds to a variation in rolling resistance of 0.6 %".

This means that a temperature difference of 20 °C will cause a change in RRC of 12 %.

In ISO 28580 a temperature correction to a reference temperature of 25 °C is specified as:

\[ F_{25} = F_r \left[1 + K(t_{amb} - 25)\right] \]

where:

- \( F_r \) is the rolling resistance, in Newtons;
- \( t_{amb} \) is the ambient temperature, in degrees Celsius;
- \( K \) is equal to 0.008 for passenger tyres
- \( K \) is equal to 0.01 for truck and bus tyres with load index 121 and lower
- \( K \) is equal to 0.006 for truck and bus tyres with load index 122 and above

This means that a temperature difference of 20 °C will cause a change in RRC of 16 %. An even higher temperature effect was reported by [Descornet, 1990]. His results are shown in Fig. 4.14.

This means that a temperature difference of 20 °C will cause a change in RRC of approx. 40 %, which is much higher than reported above. However, note that Descornet's temperature data are measured in the air inside the tyre. It means that, most likely, these results include the effect of increasing inflation due to the ambient temperature differences.

It can be concluded that even though the reported data are inconsistent, the reported temperature effects are that high that temperature is a factor that must be very closely controlled, and ideally measured RRC values should be corrected to a reference temperature, such as 20 or 25 °C. It also follows that one shall avoid measuring RRC at temperatures that differ much from the reference temperature, as corrections may be associated with too high inaccuracies if temperatures are very low or very high.

ISO 28580 specifies 25 °C as the reference air temperature (probably rather typical of a laboratory with many heat-producing facilities), but outdoors in Europe a 20 °C air temperature seems to be a much better choice. For example, the annual average temperature in Paris, France, is approx. 11 °C and in Rome, Italy it is 16 °C. This, or perhaps 1-2 degrees higher, would be rather close to the annual average temperature at which road traffic is running at these locations. Average daytime temperatures, when RR measurements are most likely to be conducted, would be 2-3 degrees higher. It is, therefore, suggested that MIRIAM uses 20 °C as the reference ambient air temperature.

---

4 [http://www.worldclimate.com](http://www.worldclimate.com)
Fig. 4.14: Influence of tyre internal air temperature on the RRC, according to [Descornet, 1990].
5 ROLLING RESISTANCE CONTRIBUTION TO VEHICLE ENERGY CONSUMPTION

5.1 Introduction
There is an interest in expressing the relative effect on fuel consumption of a relative change in rolling resistance. This relative fuel consumption effect depends on:

- The rolling resistance part of the driving resistance
- The energy efficiency of the engine.
- The type of driving (often special standard driving cycles are used)

For prediction of the fuel efficiency versus the rolling resistance, the concept of "Return Factor" was introduced [Schuring, 1980]. The Return Factor (RF) simply is the relative change in fuel consumption ($\Delta FC$) for a given change in rolling resistance ($\Delta RR$):

\[ \text{Return Factor} = RF = \frac{\Delta FC}{\Delta RR} \]

It may perhaps look as if this is a simple parameter to determine, but in practice it depends on the three items listed above, which causes it to vary due to the many parameters and their interactions in a very complex way. Anyway, estimates of the Return Factor are useful when it comes to describe the effects of reducing or increasing rolling resistance of a tyre or a pavement.

Examples of Return Factors will be given below. It is then essential to know that these estimates are very rough and the values given reflect just one combination of the three items listed on top of this section, which in turn have numerous sub-items, out of the almost infinite number of possibilities.

In MIRIAM it will be possible to study the Return Factors in more detail and to make much more comprehensive calculations in SP 2 and SP 3; for implementation in energy efficiency calculation models. The information presented here is just one snapshot at the beginning of the project based on the presently best knowledge.

But first, the relative contributions of various types of energy losses to driving resistance shall be illustrated in a couple of examples below.

5.2 Example of various contributions to the driving resistance
The ECRPD project (see Chapter 6) in the part conducted at VTI and supplemented with a national project supported by the Swedish Transport Administration, made it possible to perform experiments with both light and heavy vehicles using the coastdown method. The method was designed in a way which made it possible to determine by means of statistical procedures the relative contributions by various parameters and various energy losses. A chapter later in this report describes this method in some detail.

Results from these experiments are condensed in Fig. 5.1. Some explanations:

- The vehicles have been selected in order to have reasonably "typical" performance of today's vehicles in traffic (although the heavy ones were vehicles adapted for special tasks at VTI).
- The IRI-related component is the component of the vehicle rolling resistance which has a correlation with IRI in a multi-parameter regression analysis. Most of it is probably energy consumed in the shock absorbers but some may be caused by large-scale road unevenness-related tyre deflections.
• The MPD-related component is the component of the vehicle rolling resistance which has a correlation with Mean Profile depth (MPD), measured in accordance with ISO 13473-1, in a multi-parameter regression analysis. MPD is the most commonly used value to represent road surface macrotexture.

• The RR base component is the component of RR which is independent of the other parameters, including speed.

• The transmission rear-end component is the energy consumed in the part of the transmission which rotates with the driven wheels when the clutch is engaged and gearbox is in neutral position (which it was during the measurements).

---

Fig. 5.1: Relative contributions to the sum of air resistance and vehicle rolling resistance for a car (above) and a heavy truck (below). Latest results of calculations at VTI, based on data collected in the ECRPD and national projects.
In these diagrams, the part which is the closest to *tyre/road rolling resistance* is the sum of the MPD-related and the RR base components.

When the transmission and IRI-related parts are added, one obtains the *vehicle rolling resistance*.

Some observations from the figure follow here:

Only the air drag and the IRI-related component (mainly shock absorber losses) appear to have a significant correlation with speed.

The air drag is very important for the car and less important for the truck. The speed where air drag starts to exceed vehicle rolling resistance is approx 60 km/h for the car and higher than 90 km/h for the truck.

The IRI-related component (road unevenness) is rather small for the car compared to the MPD-related component (macrotexture), while this is not true for the truck, where the IRI-related component is relatively important and may even exceed the MPD-related component at the highest speeds.

The IRI component can never be neglected for heavy vehicles. More research about this contribution is needed, both for cars and trucks.

The transmission rear-end component is relatively important, and can by no means be neglected, as it may account for up to 15-25 % of the vehicle rolling resistance. This is a contribution which is much stronger than expected and substantial enough to justify special studies and special measures.

Note that the propulsion component of driving resistance is not included in this diagram since the test vehicles were coasted-down with no power applied.

### 5.3 Example of Return Factors

Some examples of Return Factors are given for light vehicles in the US in a table in [Gent & Walters, 2005]; see Table 5.1 below. Further US data are found in [TRB 286, 2006], where a Return Factor of 11 % for urban driving and 18 % for highway driving is reported, as an average of using four different calculation models in which RRC was varied ± 10 % from a nominal value of 0.008.

For Swedish conditions calculations were made in 2009 for this editor by Mr Bo Karlsson at VTI, using the VETO model [Hammarström & Karlsson, 1987]. The results are presented in Fig. 5.2. The car was similar to a Volvo V70, the truck was a 2-axle heavy truck with 4 drive axle tyres and 2 steering axle tyres, loaded to a GVW of 12 tons. The other truck towed a semitrailer (total of 5 axles) and had a GVW of 24 tons. The "highway" driving condition was a weighted average for traffic work on 14 highway categories, whereas the "Urban" condition used driving cycle A10, similar to U.S. FTP-72.

Based on these US and Swedish data, it seems that rounded "rule-of-thumb" values for the Return Factor of cars could be 10 % for urban driving and 20 % for highway driving, as well as 15 % for trucks in urban driving and 30 % for trucks in highway driving. These stereotype values are not recommended to be used in serious technical calculations, but may be useful to remember by heart in order to get a general feeling for the case.

Later results of MIRIAM may suggest better estimates to use.

Note that electric and hybrid vehicles are likely to have a substantially higher Return Factor.

If a model to calculate the Return Factor is available, it should always be used instead of the "rule-of-thumb" values, since the variation is so large depending on the circumstances.
Table 5.1: Return Factors for a selection of US light vehicles. The Return Factor is listed as a range between a lower and a higher value in the rightmost column. The second column from the left is fuel consumption in litres/km. To convert weight from lbs to kg, multiply the lbs values by 0.45. The calculations are based on RRC of 0.007-0.011 and on the EPA combined urban and highway driving cycles. From [Gent & Walters, 2005].

<table>
<thead>
<tr>
<th>Vehicle class</th>
<th>FE, mpg/F_L, L/km</th>
<th>Vehicle weight, lbs.</th>
<th>Calculated F_{c,th}/F_c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact</td>
<td>33/0.071</td>
<td>2800</td>
<td>0.105-0.165</td>
</tr>
<tr>
<td>Midsize sedan</td>
<td>25/0.094</td>
<td>3500</td>
<td>0.099-0.155</td>
</tr>
<tr>
<td>Large sedan</td>
<td>22/0.107</td>
<td>4200</td>
<td>0.104-0.164</td>
</tr>
<tr>
<td>Small SUV</td>
<td>20/0.117</td>
<td>3500</td>
<td>0.079-0.125</td>
</tr>
<tr>
<td>Large SUV</td>
<td>17/0.138</td>
<td>5300</td>
<td>0.102-0.160</td>
</tr>
<tr>
<td>Minivan</td>
<td>22/0.107</td>
<td>4500</td>
<td>0.112-0.176</td>
</tr>
<tr>
<td>Small pickup</td>
<td>18/0.130</td>
<td>4100</td>
<td>0.084-0.132</td>
</tr>
<tr>
<td>Large pickup</td>
<td>15/0.156</td>
<td>6000</td>
<td>0.102-0.161</td>
</tr>
</tbody>
</table>

Fig. 5.2: Example of Return Factor for three types of vehicles and two types of driving. See text for more details.
6 REFLECTIONS AND OBSERVATIONS ON ROLLING RESISTANCE MEASUREMENT AND MODELLING FROM THE ECRPD PROJECT

6.1 Introduction and objective

In the period January 2007 to January 2010, a project named “Energy Conservation in Road Pavement Design, Maintenance and Utilisation” (ECRPD) was carried out\(^5\) [ECRPD, 2010]. A large part of the work was performed by staff at VTI. The ECRPD project had many activities that are related to the subject of MIRIAM and constitutes a good starting platform for MIRIAM. Therefore, this report includes this chapter in which some of the experiences in ECRPD are discussed with a focus on present and upcoming MIRIAM activities.

The ECRPD project demonstrated the crucial importance of having access to road traffic energy models with high accuracy. An overall statement, one could say that all measures available in road construction or road maintenance which decrease road traffic energy use will also reduce total energy use for road construction and management as well as for the traffic. This conclusion is based on the relations between annual energy usage by traffic and energy usage by road construction and maintenance, which are:

For "regular" two-lane roads: \(\approx 1\)
For wide two-lane roads: \(\approx 3\)
For motorways: \(\approx 8\).

Thus, on a wide two-lane road, the annual energy usage by traffic is three times the energy usage by road construction. It suggests that energy savings should preferably be focused on energy usage by traffic and that investments for this cause in the construction may be very effective. In other words: if it costs a little extra to construct and maintain a road surface which cuts vehicle energy consumption, this may mean improved economy, and not only an improved environment. Also [Anon., 1979] arrived at such a conclusion.

The overall objective of the MIRIAM project is to provide a strategic tool for infrastructure decision makers for setting up and achieving energy-saving and \(\text{CO}_2\)-reducing goals by means of reduced rolling resistance. Doing so will allow road administrations to forecast the amount of \(\text{CO}_2\) emitted by vehicle rolling resistance in relation to pavement type and condition for a road network. In order to achieve this objective of MIRIAM there is need for:

- a rolling resistance model
- a model for other driving resistances than rolling
- a model for transmission energy losses
- a model for auxiliary equipment energy losses
- an engine model.

For all these models there is a need for quantitative parameter values.

Since MIRIAM shall consider different types of vehicle power units there is a need for more than one transmission and engine model. If other emissions than \(\text{CO}_2\) will be estimated too the degree of complexity for the engine model will increase considerably.

One main problem regarding a rolling resistance model is that there is no general principal model available which includes all variables of importance. There is also a serious lack of parameter values, especially when the objective is to develop a general model for all types of road vehicles and types of tyres. The experience from previous studies including literature surveys is that there are not much useful results available on road surface effects. Instead, the MIRIAM project will have to supply useful data.

\(^5\) Website: http://www.ecrpd.eu/ or http://www.roadtechnology.se/ecrpd.eu/index.asp?mainID=50
For the other type of resistances than rolling, the situation is considerably better with regard to availability of principal models; although still there is a lack of parameter values, including for example air resistance coefficients.

There are two types of transmission losses: churning and mechanical losses. The situation with regard to conventional transmissions is that there are rarely any data available here.

A combustion engine model is possible to base on:

- an engine map
- a max torque curve
- an internal friction drag curve.

However, obtaining useful engine data for these will require that substantial economical resources be allocated.

### 6.2 Problems to address

A major problem to solve is to formulate a rolling resistance model, including all variables of more than minor importance for rolling resistance, and to calibrate and validate such a model. In the literature one can find sub-models for some of these variables separately, or a few together, but not for all integrated into one model.

In MIRIAM the road surface effects are in focus. The potential problems, in general, when measuring and estimating driving resistance based on road surface measurements include:

- which explanatory variables to include and how to record them with good accuracy
- how to model vehicle rolling resistance
- correlations between explanatory variables in general
- different measures exist for the same type of road surface condition
- changes in the test vehicle taking place during a day and between days
- the need for control of and adjustment of tyre pressure
- variation in road surface conditions across the road, introducing an uncertainty concerning which conditions the test vehicle has been exposed to.

The explanatory variables to include in the model should primarily be those with more than minor effects on total vehicle rolling resistance. Some variables are of interest both in order to give a possibility to present results for a reference situation, and for estimation of representative rolling resistance on the road in general. One purpose of using such variables is to make measured data under different conditions presented in the literature comparable. Ambient temperature could be such a variable.

If variables of importance for vehicle rolling resistance are not considered these effects will still be there, but hidden in those parameter values that are present. Such measured results will then cause problems when trying to compare results in this study with results in the literature.

The transmission resistance includes two parts: mechanical frictional losses between the gear-wheels, and frictional losses of transmission components rotating in oil (churning losses). During coastdown with the gear box in neutral position there is essentially one part present which is considered: the oil rotating losses. However, when driving, one will need also the mechanical friction losses and measurements with a driving vehicle are not easy to perform.

---

6 By "explanatory variable" is meant a variable which has a significant influence on the results
There is a problem to separate rolling resistance and transmission resistance. The rolling resistance increases with increasing vehicle weight but the churning losses are independent of vehicle weight. By varying the vehicle weight it should then be possible to separate rolling resistance and transmission resistance. This has been tried and documented in two studies by VTI.

Especially for the road surface effect on RR, there may be more than one measure to describe the important properties. In ECRPD, several road surface measures were recorded in all measured cases. It turned out that IRI and MPD were the measures with the highest degrees of explanation in order to describe the resistance contribution from roughness and macro texture. However, there are still some unsolved questions regarding these measures:

- **IRI**: The IRI is based on a quarter-car model attempting to provide a measure which is related to the work in the suspension system caused by road unevenness, where the different wavelengths are weighted according to the response of common car suspension systems. However, there is also an effect of unevenness on tyre deflection and it is very unclear whether the IRI wavelength weighting is appropriate for this effect. This would justify more research.

- **Megatexture**: In-between the wavelengths of road unevenness (represented by IRI) and macrotexture (represented by MPD) there is a range named megatexture. This may have an influence which may be very substantial. Although megatexture has not been measured so far (but it will be so in MIRIAM), it is usually represented in data sets by the MPD measure, partly also by the IRI, since these three measures are generally well correlated when looking at a random selection of roads.

The influence of different wavelengths in the road surface profile is probably a function of:

- tyre contact patch area or contact patch length
- tyre type and inflation (which affect the contact area)
- vehicle dynamic parameters, such as spring constants of tyre and springs, shock absorber damping force as a function of vertical speed, etc.

One hypothesis could be:

- that wavelengths shorter than the length of the contact area influence RRC by a deformation of the contact area
- that wavelengths longer than the contact area influence RRC by effects, such as losses in the suspension; possibly also by vertical movement of the full vehicle

Examples of rather typical tyre contact area lengths are 0.15 m for a car tyre and 0.25 m for a heavy vehicle tyre; of course depending largely on the tyre dimension. The contact patch length will change with changing tyre load and with inflation. One could then assume that there is not one limit value between these different types of contributions to RRC; rather that for the same vehicle there would be different proportions between the short and long wavelength effects for different vehicle load.

There is a definition problem how to describe the road roughness effect on vehicle rolling resistance. For road measurements with trailers or full vehicles there will always be a dynamic effect from the vehicle as a part of the additional resistance. The same tyre will give different results when used on different vehicles.

Even if one uses standardized measures for road surface conditions with high assumed degree of explanation for vehicle rolling resistance, problems can follow from the variation in conditions across the road. Standardized measures for road surface conditions represent just these special positions across the road where measurement takes place. In the ECRPD project the following positions were used:
• IRI was measured in two tracks: one in the left wheel track and one 1.5 m further to the right
• MPD was measured in three tracks: one in the left wheel track, one 1.5 m to the right and one between the two first tracks

The width between the tyres is more than 1.5 m for a 60 ton articulated truck. The impact of road surface conditions on the motion of the vehicle will depend on the side position of the vehicle and the width between the wheels on the left and right side. For heavy vehicles with four wheels on the rear axle there will be a difference between road condition exposure for the wheels on the front and rear axle. There may also be different exposure for the truck and the trailer depending on different average widths between the wheels. If rolling resistance effects are estimated based on measurements in an ideal situation, the lateral position for each wheel and the road conditions in these positions should be known along the test route.

There will be a continuous change of the test vehicle during measurements; at least regarding vehicle weight. The amount of fuel in the tank will change as the vehicle is driven, which results in a systematic variation by time. This effect should be controlled since it can be done with small efforts.

Other facilities which are not that easy to control and adjust for are the braking system and the tyre conditions. Tyre conditions include tyre wear, tyre temperature and tyre inflation pressure. During a measuring program there could be a total driving distance of for example 1000 km. The rolling resistance will normally decrease with increasing tyre wear; i.e. with thinner tread. Even if driving 1000 km will cause just a marginal wear there will be an effect. The brakes may, if not well maintained, not release fully, which might be heard, which will cause an extra energy loss in terms of heat.

Another major problem when measuring rolling resistance is how to select, adjust and set tyre inflation pressure. Increasing tyre pressure reduces rolling resistance. The tyre pressure is a function of:
• atmospheric air pressure: increasing air pressure will decrease the tyre over-pressure
• ambient air temperature: increasing air temperature will increase the tyre pressure
• rolling resistance: increasing rolling resistance will increase the tyre temperature and thus the tyre pressure

These changes will take place during measurements if there are no adjustments of the tyre pressure.

Tyre temperature not only affects tyre pressure but also directly affects rolling resistance.

The amount of load can influence tyre pressure in two ways:
• increasing load will most probably increase tyre temperature which in turn will increase tyre pressure
• there is a possibility that a change of load somewhat influences tyre pressure at stand still, at the same tyre temperature. As inflation pressure has a high influence on RR, even a minor pressure change may be necessary to control. The interest in such an effect is for control and adjustment of tyre pressure at change of load.

One further point of interest for the test design is how to handle a possible leakage of tyre inflation gas, causing a gradual decrease in inflation pressure. Possible alternatives for tyre pressure adjustments are:
• inflation adjustment for leakage only
• inflation adjustment for all deviations from the desired pressure, including temperature effects; measurements are always made at the same tyre pressure
• adjustment for the load
The first alternative means that there will be different tyre pressures for different parts of the measurements as a function of ambient temperature, tyre warm-up and air pressure variations, even if there is no leakage. In order to handle this there is a need for modelling of tyre pressure changes to find the control pressure, the pressure there should be without a leakage. In practice this alternative is difficult to fulfil.

In the ECRPD, the tyre pressure was adjusted to the same level before entering each test route, which means the second alternative above. Since the test routes had different surface properties the tyre temperature and the pressure changed from test route to test route even if the initial pressure per test route was kept constant. It also meant that inflation pressure was allowed to change between adjustment occasions, i.e. during the measurements on the test site. Such pressure changes could take part since the vehicle was never running in a constant mode with exactly the same rolling losses. It should be obvious that even this alternative has its problems.

It should be noted that frequent controls and adjustments of tyre inflation on an articulated truck are most time consuming to perform, which itself will lead to a change in vehicle operation and temperature.

Ideally, the estimated RRC should be representative for the normal use of the test vehicle. In regular daily vehicle operation, drivers are instructed to make tyre pressure adjustment for “cold” tyres. One could expect that there is a time period of at least a day or in many cases some weeks or even months between tyre pressure adjustments during normal use of a vehicle in traffic. The above mentioned adjustments of pressure are thus not really corresponding to normal use of the vehicle. Instead, they are ideal test conditions attempting to make repeatable and reproducible measurements, rather than measuring “typical” RRC values. This is of course an arguable measurement policy.

The cross fall of the road will influence the lateral force distribution. For example, higher vertical force (load) on the right side (due to centre of gravity being slightly displaced when there is cross fall) is expected to give somewhat higher tyre temperature and pressure on the right hand side of the vehicle.

The cross fall causes an extra driving resistance (F_{side}) because the tyre will not be running perfectly parallel to the vehicle movement direction. $F_{side}$ is a function of tyre cornering stiffness (CA). CA is a non-linear function of the tyre load. Because of the cross fall one can expect different $F_{side}$ on different wheels on the same wheel axle.

The rolling resistance is higher when a wheel is driven than when it is free-rolling [Gent and Walter, 2005]. This might mean that testing with only free-rolling wheels is not perfectly representative of actual driving. Road surface effects estimated from fuel consumption measurements include a mix of freely rolling and driving wheels while coastdown or trailer measurements only include free rolling wheels.

Another type of problem is how to develop a general tyre model based on the literature and on own measurements. General problems include:

• rolling resistance differs between tyre brands of the same dimension
• rolling resistance differs between tyres having different dimensions
• rolling resistance changes as a function of a change in tread depth
• rolling resistance differs between freely rolling and driven wheels
• rolling resistance coefficient may be changing with tyre load, although it is mostly assumed not to do so
• rolling resistance may be different for different vehicles for the same set of tyres, since roughness may cause more or less losses in the shock absorbers (a problem common to most measurement methods)
• rolling resistance effects due to road surface variations might change with the factors mentioned above.
The test vehicle represents a part of the measuring system. The measuring system should not vary by time, at least not without control. Using coastdown measurements, compared to fuel consumption measurements, should reduce the risk for a change in the measuring system by time since the influence of the engine and a variation in fuel qualities is excluded.

The crucial point is how one can develop a general model that takes all important parameters into account, without having to make measurements with a large number of tyres run on a large number of road surfaces, since resources for the latter are not available.

6.3 What to include and not include in a tyre/road rolling resistance model

The following losses should not be included in a tyre/road rolling resistance model:

- Losses in bearings
- Losses in the transmission
- Losses in the wheel brakes
- Losses caused by air resistance of the wheel (tyre and rim) when moving

The three first items are part of vehicle rolling resistance, as they are active when the vehicle is rolling, and the last item is part of the vehicle air resistance, but none of them shall be included in tyre/road rolling resistance.

Furthermore, there is also air resistance for the rotating tyre. These losses are proposed to be included in tyre/road rolling resistance as it is an effect clearly limited to the tyre rolling and rotation.

The following list includes a few types of "separable" energy losses that need special concern in upcoming measurements and in development of a tyre/road RR model:

- Energy losses in the tyre, excluding side force effects
- Energy losses caused by side force
- Energy losses due to limited stiffness and elasticity of pavements, in particular on unbound road materials and on bituminous pavements in hot weather (causing hysteresis losses)
- Energy losses due to water or snow on the road

A delicate problem is which of the effects that road unevenness (wavelengths longer than 0.5 m) has on energy losses in the vehicle that shall be considered part of tyre/road rolling resistance. The known effects are:

- Deflection and associated hysteresis losses in the tyres
- Movements in the vehicle suspension system and damping losses in the shock absorbers
- Air resistance effects from the vertical and rotating movements of the vehicle as it bounces up and down and is tilted when following the unevenness in the two wheel tracks on the road (this refers mainly to the sprung mass of the vehicle).

The only one of the above that is clearly part of tyre/road rolling resistance is the first one. The second one is part of vehicle rolling resistance, but whether the last one should be considered as a part of the air resistance or part of vehicle rolling resistance is not absolutely clear. In any case, when making measurements it is almost impossible to distinguish between the three components. Even when using the trailer method, it is impossible to distinguish between the tyre hysteresis effect and the losses in the shock absorber of the trailer; unless one would attempt to measure the latter by (for example) means of temperature analyses.

In the ECRPD project it was believed that there are also other losses caused by road unevenness which still have not been identified and explained.
The possibility to isolate RR from other energy loss components depends to a high degree on the measuring method used. The possibility to isolate RR will be enhanced by using the various methods, where the following order may be the most promising:

- Laboratory drum
- Trailer
- Coastdown
- Fuel consumption (not so useful for this purpose)

For all types of measurement campaigns, there is a need for measurements of all variables describing the pavement, road condition (wet, humid, dry, patchy, etc), the road topography, the tyre properties and condition (such as tread depth, spring and damping constants, dimensions, weight, etc), tyre temperature and the ambient conditions, which are not estimated to have a negligible influence. This should be made as close in time as possible as, for example, the ambient conditions may change very fast. Only by doing these extensive measurements will it be possible to develop a proper RR model that may be valid for most conditions.

There is need to determine a set of reference conditions when measuring tyre RR. These conditions are proposed to be selected as similar as possible to existing standardized measuring methods and to common conditions in the regions where MIRIAM partners are located. These conditions should include:

- A horizontal, plane (even) and stiff road surface
- An ambient air temperature of 20 °C (ISO 28580 specifies 25, but note that this is indoors in a hall often heated up by tyre tests)
- A tyre load of 80 % of tyre load index (LI)
- A free-rolling wheel.
7 MEASUREMENT METHODS - GENERAL

7.1 Rolling resistance
Measurement methods and equipment for rolling resistance are the primary focus of SP 1 of MIRIAM. The methods which are available can be grouped into four general categories:

- **Laboratory drum (DR) method**: Laboratory measurements made with test tyres rotating on drums. The drums may be equipped with sandpaper or replica road surfaces, apart from the steel surface of the drum.
- **Trailer (TR) method**: Measurements with test tyres rolling in a special towed trailer. The trailer may be designed either for passenger car tyres or for heavy truck tyres.
- **Coastdown (CD) method**: Coastdown measurements using any type of vehicle, measuring deceleration and a number of other parameters, from which rolling resistance may be calculated. The test vehicle is coasted (gearbox in neutral) from one higher to one lower speed.
- **Fuel consumption (FC) method**: Fuel consumption measurements using especially instrumented (normal) vehicles, from which rolling resistance may be calculated by means of a fuel consumption/rolling resistance model. A variant of this would be when using a vehicle not powered by fuel, such as an electric vehicle. Then the method should be called Energy Consumption (EC) method instead. Note that driver influence might be high in this method.

These methods can be supplemented by additional measurements of e.g. suspension forces. However it is necessary to realize that the choice of the measurement method implies also some assumptions and limitations concerning the model derived from the results. The main challenge in most cases consists in the difficulty of isolating the effects of rolling resistance from other contributors to the total driving resistance and fuel consumption.

7.2 Test objects: tyres or pavements?
Depending on whether the intention is to measure RR of tyres, for some given reference surface(s), or to measure RR of pavements, for some reference tyre(s), the choice of method may be different.

If tyres are in the focus, the drum method would most likely be used, as there is an ISO standard for it. However, the trailer method would be equally useful, if one is prepared to measure under real road conditions rather than the artificial laboratory conditions, and it should at least be used for validating the laboratory measurements. The coastdown method may also be used for tyre measurements. However, it requires control over some more measurement and vehicle parameters, and also requires 4 test tyres instead of a single one.

If pavements are in the focus, the drum method can be used only if it is possible to put the pavements under study on the drum, and in a way which preserves their stiffness. It is possible but may require a lot of work to produce the drum covering surfaces. The trailer and the coastdown methods will be the most useful and practical. The fuel consumption method is also possible, but it requires control of factors related to the fuel and the engine, in addition to the data needed when conducting the coastdown method. It is more difficult to separate out the RR values, and the engine introduces another hard-to-control factor in the measurements.

7.3 Measurement of pavement-related parameters
The experimental work planned in SP1 and proposed in FP7 aims at measurement methods which form a consistent and clearly defined basis for modelling.

Rolling Resistance – Basic Information and State-of-the-Art on Measurement methods
Editor: Ulf Sandberg (VTI)
To this end all parameters related to the pavement, operational and ambient influence on the measured values should be collected. These include:

- Longitudinal profile of the test section, analysed in third-octave band levels
- Transversal profile of the test section (to see if there are ruts)
- IRI
- Megature level
- MPD
- A microtexture-related measure, such as BPN (British Pendulum Number)
- A stiffness-related measure, such as hysteresis curve measured by means of FWD
- Longitudinal gradient of the test section
- Transversal gradient of the test section (has an effect on side forces)
- Ambient air temperature
- Test tyre temperature
- Road surface temperature
- Data for the test tyres must be available (dimensions, tyre pressure, shore hardness, tread depth, balance, pre-measurement conditioning, warm-up)
- The rim must be specified/described (dimension, construction, material)

Ideally, in the modelling work, all of the parameters above should be measured very close in time with the rolling resistance measurements. If the purpose is not to contribute to the modelling but just to survey a number of road sections, one may limit the measurements to a smaller selection, depending on the features of the road sections.

All these parameters may not be needed for all the methods, and for all test sections, but one should in advance make a checklist of what is needed and then make sure that equipment is available for the measurements.

There are some instrumented vehicles that may measure most of the parameters above, such as the VTI RST vehicle, see Fig. 7.1, which will be used extensively in MIRIAM. A vehicle instrumented with lasers to measure specifically the road surface texture is shown in Fig. 7.2, another one is shown in Fig. 7.3.

![Fig. 7.1: The RST vehicle from VTI, equipped to simultaneously measure most of the geometrical features of a road surface.](image)

**Fig. 7.1:** The RST vehicle from VTI, equipped to simultaneously measure most of the geometrical features of a road surface.
Fig. 7.1: Road surface texture measurement vehicle. (1) triple-laser construction, (2) camera, (3) control unit.

Fig. 7.3: The VTI laser profilometer, in operation in Hong Kong (stopped for calibration). A speed encoder is mounted on the right rear wheel. The equipment is possible to move and travel with, provided a host vehicle is available such as the Nissan Pathfinder in this picture.
8 MEASUREMENT METHODS – STANDARDS

8.1 Introduction
There are international or industry standards only for measurement of rolling resistance of tyres. No standard or common practice has been published for measurement of rolling resistance properties of pavements. All of the existing (and earlier ones) are based on laboratory drum measurements.

A typical laboratory test for rolling resistance consists of a test drum, a cylinder aligned with the center of the drum, and a tyre to be tested. The tyre is held against the drum, which is run by a motor coupled to it. The tyre’s rolling resistance applies a braking effect to the drum’s rotation, and this effect is translated into measurements of forces, torques, decelerations, etc. Rolling resistance is then calculated from these measurements. Figure 8.1 shows the configuration of this procedure [Gent & Walters, 2005]. The Society of Automotive Engineers (SAE) and the International Organization for Standardization (ISO) have both prescribed test standards for this procedure.

![Fig. 8.1: Typical test configuration for tyre rolling resistance. From page 516 in [Gent & Walters, 2005].](image)

The test standards for rolling resistance include four common measurement methods (although not all of them are in each standard). These measurement methods include:

- measurement of the resistive force at the tyre spindle (force method)
- measurement of the resistive torque on the drum hub (torque method)
- measurement of the electrical power used by the motor to keep the drum rotating (power method)
- measurement of deceleration after the driving force at the drum is discontinued (deceleration method).

During the measurement of rolling resistance, aerodynamic drag, which can account for up to 15 % of the laboratory measurement of rolling resistance [Gent & Walters, 2005], may need to be measured and subtracted from the result, and this is commonly though not always done. Because the magnitude of aerodynamic drag on the tyre in a laboratory test differs significantly from that on an actual vehicle, the inclusion of aerodynamic drag in laboratory tests makes the results unrepresentative of the real situation. However, because there are practical limitations on the measurement of aerodynamic drag in some test methods, such as techniques to remove systematic errors associated with machine offset [Gent & Walters,
In addition to the measurement methods, the number of testing points can also differ, depending on the test condition. A single-point test includes only one setting for tyre pressure and tyre load, while a multi-point test includes a series of settings of tyre pressure and tyre load. Rolling resistance is then calculated from the regression of the multi-point measurements. Different testing standards prescribe different numbers of testing points.

As mentioned before, there are several test standards to define the measurement conditions, including two set by the Society of Automotive Engineers (SAE), SAE J1269 and SAE J2452, and two set by the International Organization for Standardization (ISO), ISO 18164:2005 and ISO 28580:2009. These standards are used extensively in the tyre and automotive industries for rolling resistance measurement. Table 8.1 compares the available drum methods.

Table 8.1: SAE and ISO standards for measurement of rolling resistance of tyres.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Test point</td>
<td>Single-point</td>
<td>Multi-point</td>
<td>Multi-point</td>
<td>Single-point</td>
</tr>
<tr>
<td>Measurement methods</td>
<td>Force, torque, power</td>
<td>Force, torque, power</td>
<td>Force, torque, power, deceleration</td>
<td>Force, torque, power, deceleration</td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>Force</td>
<td>Force</td>
<td>Energy loss per distance</td>
<td>Energy loss per distance</td>
</tr>
<tr>
<td>Road/wheel diameter</td>
<td>1.7 m</td>
<td>1.7 m</td>
<td>1.219 m or greater</td>
<td>1.5 m or greater</td>
</tr>
<tr>
<td>Road/wheel surface</td>
<td>Medium-coarse texture</td>
<td>Medium-coarse texture</td>
<td>Medium-coarse texture</td>
<td>Smooth (texture optional)</td>
</tr>
<tr>
<td>Temperature range</td>
<td>20 to 28 °C</td>
<td>20 to 28 °C</td>
<td>20 to 28 °C</td>
<td>20 to 30 °C</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>24 °C</td>
<td>24 °C</td>
<td>24 °C</td>
<td>24 °C</td>
</tr>
<tr>
<td>Speed</td>
<td>80 km/h</td>
<td>80 km/h</td>
<td>Coastdown; 115 km/h to 15 km/h</td>
<td>80 km/h</td>
</tr>
</tbody>
</table>

SAE J2452, ISO 18164:2005, and ISO 28580:2009 all adopt the concept of "energy loss per distance travelled" as the definition of rolling resistance, but note that it is equivalent to a drag force with the unit Newton. For measuring the rolling resistance of truck tyres, drums with greater diameter (2.70 m) are used too.
8.2 SAE

8.2.1 SAE J1269: Rolling resistance measurement procedure for passenger car, light truck, and highway truck and bus tires

SAE J1269 is an industry standard that was originally approved in 1979 as a method for determining rolling resistance at four different load and pressure conditions for passenger car tyres, six test conditions for light truck tyres, and five test conditions for truck and bus tyres. In this standard, rolling resistance is defined as “the scalar sum of all contact forces tangent to the test surface and parallel to the wheel plane of the tyre.” This is the only standard that still uses a force-based concept for rolling resistance; however, because it is the first standard for testing rolling resistance and it has been extensively used in rating and reporting systems, many existing studies are still based on test results from it.

The latest version of this standard includes both a multi-point test procedure and a single-point test procedure at the standard reference condition. Force, torque, and power methods are adopted in this standard for rolling resistance measurement.

8.2.2 SAE J2452: Stepwise coastdown methodology for measuring tire rolling resistance

As indicated in the title, this test standard consists of a coastdown approach. In this test, the tyre is first operated at a certain speed. After the first measurement is made, the wheel speed is reduced and a second measurement is made. This procedure is repeated until a minimum of six measurements have been made. This method is designed to simulate the range of speeds in the EPA's Supplemental Federal Test Procedure (SFTP) for vehicle fuel economy, but not to account for the rolling resistance during acceleration and deceleration [Tiax, 2003].

This standard only uses a multi-point procedure, with four test conditions for passenger cars and five for light trucks. Only the force and torque methods are included in this standard. A single-point result based on the standard reference condition can be calculated later.

8.3 ISO

8.3.1 Past and present ISO standards

Over the years, ISO standards for measurement of rolling resistance have existed according to Table 8.2. The three first ones have been withdrawn in connection with ISO 18164 being published; as the latter replaces them all.

Table 8.2: ISO standards for measurement of rolling resistance

<table>
<thead>
<tr>
<th>Number</th>
<th>Title</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 8767:1992</td>
<td>Passenger car tyres -- Methods of measuring rolling resistance</td>
<td>Withdrawn</td>
</tr>
<tr>
<td>ISO 9948:1992</td>
<td>Truck and bus tyres -- Methods of measuring rolling resistance</td>
<td>Withdrawn</td>
</tr>
<tr>
<td>ISO 18164:2005</td>
<td>Passenger car, truck, bus and motorcycle tyres -- Methods of measuring rolling resistance</td>
<td>In force</td>
</tr>
<tr>
<td>ISO 28580:2009</td>
<td>Passenger car, truck and bus tyres -- Methods of measuring rolling resistance -- Single point test and correlation of measurement results</td>
<td>In force</td>
</tr>
</tbody>
</table>
It appears that there are two ISO standards available for the same purposes. In most technical aspects they are the same (see more below). This may be very confusing.

The new EC regulations require the use of ISO 28580. The NHTSA in USA have recommended the use of the same. Nevertheless, it is understood by the authors that the 18164 still is used frequently by organizations doing testing for the tyre industry, such as the TÜV Automotive in Germany.

8.3.2 ISO 18164:2005: Passenger car, truck, bus and motorcycle tyres — Methods of measuring rolling resistance

This is a test standard set by ISO and is very similar to SAE J1269. The major differences are that this method includes all four measurement methods — force, torque, power, and deceleration — and this standard only uses a multi-point test, with four test conditions for passenger cars and five for light trucks.

8.3.3 ISO 28580:2009: Passenger car, truck and bus tyres — Methods of measuring rolling resistance — Single point test and correlation of measurement results

This is a new rolling resistance test standard recently set by ISO. All four measurement methods are available for this standard, and it uses a single test point based on the tyre load. The novelty of this standard is that it contains a detailed method of lab alignment; which is a kind of Round Robin Test (RRT). This is intended to bring all participating laboratories to measure the same reference level of RR for the set of (two) tyres. The RRT procedure in the draft version of this standard requires two reference tyres for passenger cars and smaller light truck tyres. The tyres are to be tested on a reference machine, then sent to a candidate lab that will use the tyres to calibrate its measurement with the reference lab. The correlation develops an alignment equation for the reference lab to correct its data. The reference tyre must then be run (three separate measurements) at a maximum interval of one month to maintain alignment. The full alignment process must be repeated every two years.

8.4 Other standards

In principle, one could imagine a method being used which is based on any of the SAE or ISO standards, but where the drums are a dynamometer, either single or double, on which a vehicle may be positioned, to allow the vehicle to drive or roll on the drum(s), in which case one can measure in a more realistic way.
9 MEASUREMENT METHODS AND EQUIPMENT – LABORATORY DRUM

9.1 Measurements at BASt, Germany

9.1.1 General
At the Bundesanstalt für Strassenwesen (BASt) in Bergisch-Gladbach, there is a large facility for making RR measurements, as well as a number of other tyre/road interaction measurements, such as noise. The facility is based on a drum having an inner diameter of 5.5 m, on the inside of which replica road surfaces can be mounted, as desired. See Fig. 1. An example of such a casket with road surface mounted in it is shown in Fig. 9.8. In this way, very realistic pavements of normal thickness may be constructed. The joints between the caskets must be adjusted to reduce any irregularities that may cause tyre vibrations. The drum unit has a weight of 40 tons and is fixed to a central shaft by twelve spokes and is driven by a 350 kW linear motor with a maximum speed of 270 km/h. The spokes are covered by sheet metal plates on the back side and are covered by absorbing foam material on the front side to avoid air turbulences on one hand and noise reflections on the other hand.

Fig. 9.1: Tyre/pavement interaction test facility ("PFF") for laboratory rolling resistance measurements at BASt in Germany.

9.1.2 Description of the test procedure for rolling resistance measurements of truck tyres (procedure used at the PFF with the coastdown method)
The following stepwise procedure is followed when doing RR measurements at the BASt PFF facility:

1. Determination of rotating moment of inertia of the tyre:
   a. Weighing the complete wheel (tyre and rim)
b. Determination of the rotating moment of inertia via a bifilar pendulum (see Fig. 9.2): measurement of the time for 5 oscillations and calculating the average.

c. Calculation of the moment of inertia of the tyre and rim according to the following formula in ISO 28580:

\[ J_R = \tau^2 \cdot \frac{m_R \cdot g \cdot a \cdot b}{4 \cdot \pi^2 \cdot h} \]

Fig. 9.2: Sketch of a bifilar pendulum for determining the rotating moment of inertia of a wheel (source: ISO 28580).

2. Determination of the rotating moment of inertia of the test drum with installed surface cassettes and an additional mass by oscillating the whole system.

3. Inflating the truck tyre according to ISO 28580 (corresponding to maximum load capacity for single-tyre application).

4. Warming-up the tyres according to ISO 28580; depending on load index LI of the tyre:
   - 50 min for tyres with LI less than 121
   - 150 min for tyres with a rim diameter smaller than 22.5” and an LI above 121
   - 180 min for tyres with a rim diameter of 22.5” or more and an LI above 121

The truck tyres are inflated corresponding to the maximum load capacity for single-tyre application.

5. Test speeds according to ISO 28580; depending on load index and speed symbol of the test tyre:
   - for LI \( \leq 121 \) test speed is 80 km/h
   - for LI > 121 and speed symbol J or no speed symbol: 60 km/h
   - for LI > 121 and speed symbol K and higher: 80 km/h
6. Tyre/wheel – load according to ISO 28580 (85 % of maximum capacity).

7. Performing coastdown measurements: measurement of time duration during which the whole system (wheel and drum) needs to decelerate \([v_{\text{Test}} + 5 \text{ km/h} ; v_{\text{Test}} - 5 \text{ km/h}]\).

8. Performing deceleration measurements of the test drum without the tyre in the given speed interval; to determine parasitic losses due to bearing friction and aerodynamic resistance.

9. Performing deceleration measurements of the tyre without contact to the test surface; to determine parasitic losses due to bearing friction and aerodynamic resistance.

10. Calculation of the rolling resistance force \(F_{RR}\) using the following formula:

\[
F_{RR} = \left( \frac{J_{PFF}}{r_{PFF}} + \frac{J_{R_{gys}}}{r_{R}^2} \right) \cdot \alpha - \frac{J_{PFF}}{r_{PFF}} \cdot \alpha_{PFF_0} - \frac{J_{R_{gys}}}{r_{R}} \cdot \alpha_{R_0}
\]

where \(\alpha\) = angular deceleration.

9.1.3 Description of the test procedure for rolling resistance measurements of passenger car tyres (procedure at the PFF with the direct force measurement)

For passenger car tyres the method for measuring rolling resistance at the PFF of BASt is the direct force measurement as described in ISO 28580.

1. Warming up the test tyre according to ISO 28580 (30 minutes) at described test load (80 % of maximum load capacity of the tyre) and at 80 km/h with a cold tyre pressure of 210 kPa for standard load and 250 kPa for reinforced tyres.

2. Due to the construction of the wheel suspension at the PFF and to the fact that an inner drum test facility has a curvature, the longitudinal force \(F_X\) at the tyre contact patch cannot be measured directly (see Fig. 9.3). Additionally, there are other influences on the measured value of \(F_X\) (bearing friction, air drag caused by wind turbulences of the tyre/wheel combination, influence on the longitudinal force caused by a false vertical position of the wheel suspension, electrical and mechanical offset or zero drift of the force transducer used) on the measurement value of \(F_X\). The general relation for the longitudinal force is:

\[
F_X = R + F_W + F_B + F_{XZ} + F_O
\]

with

- \(R\) rolling resistance force
- \(F_W\) air drag and wind turbulence loss
- \(F_B\) bearing friction
- \(F_{XZ}\) influence on longitudinal force
- \(F_O\) zero drift of force transducer

Provided that there is a linear relation between tyre load \((F_Z)\) and longitudinal force \((F_X)\) for a certain tyre/road combination, a so called "two point measurement" is used to eliminate the additive parts of \(F_X\) which are not causally associated to the rolling resistance force \(R\). The two points are called "high" and "low". See Fig. 9.4.
To define the unknown influence $F_{xz}$ on the longitudinal force caused by a suboptimal alignment of the wheel suspension (Fig. 9.5), a calibration run at a very low drum speed and for both rotating directions before each measurement run is carried out. For very low tyre load $F_{z \text{low}}$ the value of $F_{xz \text{low}}$ can be neglected.

3. The two-point measurement procedure is used at 80 km/h and a high tyre load $F_{z \text{high}}$ (near tyre load as described in ISO 28580) and at a low tyre load $F_{z \text{low}}$ (ca. 200 - 300 N). To assure the correct ISO tyre load the values for $F_{z \text{high}}$ and $F_{xz \text{high}}$ are translated to 80 % of $F_{z \text{max}}$.

4. The rolling resistance force is calculated as follows

$$R = F_{x \text{(80\%)}} - b - F_{xz}$$

with

- $F_{x \text{(80\%)}}$ longitudinal force at 80 % tyre load
- $b$ $F_{x}$ - axis intercept

$F_{x \text{(80\%)}}$ = $F_{x} \text{ (ISO value)}$

$F_{z}$ = $F_{D} \cos \alpha$

$F_{X}$ = $F_{D} \cos \alpha$ (angle betw. wheel plane and diagonal link)

$F_{x \text{high}} = R + F_{w} + F_{B} + F_{xz \text{high}} + F_{o}$

$F_{x \text{low}} = F_{w} + F_{B} + F_{xz \text{low}} + F_{o}$

$F_{x \text{high}} - F_{x \text{low}} = R + F_{xz}$

Fig. 9.3: General force relations at the inner drum test facility PFF.
9.2 Measurements at TÜV, Germany
TÜV Automotive in Munich, Germany, has 10 laboratory drums for RR measurements. Eight of them have a diameter of 2.0 m, two of them have a diameter of 1.7 m. All the drums have a smooth steel surface.
Different tyres tested on these steel surfaces may give dramatically different friction after a warm-up period, from close to zero to up to 1.0 of friction coefficient (dry surface).

9.3 Measurements at TUG, Poland

9.3.1 General
The Technical University of Gdansk has a facility with two laboratory drums for rolling resistance measurements. They can also be used for tyre/road noise measurement. The smaller of two drums has a diameter of 1.7 m and is used for testing car tyres. The larger one has a diameter of 2.0 m, is much heavier and is used for testing truck tyres.
Figs. 9.6 and 9.7 show these two drums.
Fig. 9.6: Rolling resistance and noise testing facility at TUG in Poland. The picture shows the smaller drum, used for testing car tyres.

Fig. 9.7: Rolling resistance and noise testing facility at TUG in Poland. The picture shows the larger drum, used for testing truck tyres. The original steel surface is exposed on this picture.
9.3.2 Measurement procedure
TUG is using an own procedure, which resembles that of ISO 28580 (see BASl above), but differs in the following respects:

TUG has the following drum surfaces:

On the small drum for car tyres (1.7 m diameter):
- A sandpaper surface, purchased from 3M and having the brand name "Safety Walk"
- A rough-textured surface, imitating a surface dressing with 11 mm max. aggregate. The surface is purchased from France in the form of a "semi-flexible carpet" by the brand name "APS"

On the larger drum for truck tyres (2.0 m diameter):
- A sandpaper surface, purchased from 3M and having the brand name "Safety Walk"
- A smooth-textured replica road surface made in epoxy, imitating an ISO 10844 surface with 8 mm max. aggregate size.
- A medium-textured replica road surface made in epoxy, imitating an SMA with 11 mm max. aggregate size.
- TUG expresses F and c as values corrected to a flat surface, according to formula given in the ISO 28580
- TUG uses as reference temperature 24 °C, rather than 25 °C (because SAE uses 24 °C)
- Values are temperature corrected; for temperature correction they use K = 0.006 for all tyres (ISO specifies different coefficients for different tyre classes)
- Tyre inflation pressure is regulated at 210 kPa in warmed-up condition
- Warm-up procedure is run until the inflation stabilizes at 210 kPa

For special projects, somewhat different settings have been used.

The reason why TUG does not yet follow ISO standards fully is that TUG started to measure RR before any RR standards were available; thus TUG had to develop an own standard. So far, it has been important to follow the same original standard in order to get full compatibility between new and old RR measurements. However, it is no problem to use the ISO standards and this is sometimes done when required.

9.4 Drum surfaces
Although BASl and TUG do not use the smooth steel drum as a test surface, it is possible to do so when it is needed, but it requires removing the replica road surface.

Fig. 9.8 shows typical caskets used at BASl for fitting "real" road surfaces on the interior drum. Fig. 9.9 shows a picture of the two replica road surfaces utilized on the larger of the TUG drums.
Fig. 9.8: Caskets with road surface plates to be mounted in the BASf PFF drum. Each one is approx. 1 m long and 18 caskets are needed to cover the circumference.

Fig. 9.9: The two replica road surfaces for use on the larger drum used for testing truck tyre rolling resistance and noise emission.
9.5 Effect of drum curvature

ISO 28580 writes that correction for drum curvature may be made according to this formula:

\[ F_{r02} = K F_{r01} \]

with

\[ K = \sqrt{\left(\frac{R_1}{R_2}\right)^2 \left(\frac{R_1 + r_\tau}{R_1 + r_\tau}\right)} \]

where:
- \( R_1 \) is the radius of drum 1, in meters;
- \( R_2 \) is the radius of drum 2, in meters;
- \( r_\tau \) is one-half of the nominal design tyre diameter, in meters;
- \( F_{r01} \) is the rolling resistance value measured on drum 1, in Newtons;
- \( F_{r02} \) is the rolling resistance value measured on drum 2, in Newtons;

However, this relation was worked-out some 30 years ago, in the USA using bias ply tyres, so it is based on obsolete data. Therefore, a new relation has been worked out at the University of Karlsruhe [Freudenmann et al, 2009]:

\[ F_{R,nt} = \frac{1}{\sqrt{1 + \frac{r_{tire}}{r_{drum}} \left(0.1946 \frac{p}{F_{load}}\right)}} F_{R,drum} \]

where \( p \) = inflation pressure and \( F_{load} \) is the tyre load. The one above has the same relation for all tyres. However, it was found that by introducing a tyre factor one could get better results:

\[ F_{R,nt} = \frac{1}{\sqrt{1 + \left(\frac{r_{tire}}{r_{drum}} \left[-0.0116 + 0.3831 \frac{h_{tire}}{w_{tire}} \frac{p}{F_{load}}\right]\right)}} F_{R,drum} \]

where \( h_{tire} \) is the tyre height and \( w_{tire} \) is the tyre width; together they are simply the aspect ratio of the tyre.

With this new formula (the last one) the error in the conversion of values from one drum to the other is reduced by a factor of 2 to 5, when the errors are expressed as standard deviations [Freudenmann et al, 2009]. The new equations are worked out based on measurements on two drums with diameter 2.0 and 1.7 m and a flat surface test bed. It is not known if they would be valid also for smaller or larger drums.

9.6 Measurements at IKA / RWTH Aachen University, Germany

At the Institut für Kraftfahrzeuge (ika), at the RWTH Aachen University, in Aachen, Germany, there is a laboratory facility for making RR measurements on two drum test rigs; see Fig. 9.10.
Fig. 9.10: Tyre test rigs at ika in Aachen: 2.5 m diameter drum for truck tyre measurements on the left and 1.7 m diameter drum for car tyre measurements on the right [Bachmann, 2011].

9.7 Laboratory facilities at other places
Apart from the equipment described in this chapter, there are laboratory drum facilities for measurement of rolling resistance at a large number of places in the world, especially in Europe and North America.
10 MEASUREMENT METHODS AND EQUIPMENT – TRAILER METHOD

10.1 General about the trailer method

In the early 1980's, the Belgian Road Research Centre (BRRC) designed and built a special trailer for rolling resistance measurement. It might have been the first of its kind. Comprehensive measurements with this trailer are reported in [Descornet, 1990]. Fig. 10.1 shows the trailer and illustrates its measuring principle.

![Fig. 10.1: The original rolling resistance trailer at BRRC in Belgium (above) and the measuring principle.](image)
10.2 The TUG trailer

The Technical University of Gdańsk (TUG) designed and built a test trailer for rolling resistance measurements of passenger car tyres in the late 1990's, but first "production" measurements were made around 2005. The idea with this construction was taken from the original BRRC trailer shown in Fig. 10.1, but TUG developed it further and improved the concept in several ways. Some of the constructions are patented, and it has been improved continuously during the past 10 years. The TUG trailer in its condition of 2010 is shown in Fig. 10.2.

The trailer is designed to be towed by a reasonably powerful passenger car. The construction of the trailer is self-supporting (three-wheeler) which means that the trailer may be easily connected/disconnected from the towing car. The front wheels that stabilize the trailer have self-aligning properties. The hydraulic brake system of the trailer is operating on front wheels only and provides efficient braking of the trailer during transportation and tests. Trailer construction assures good stability of the trailer. Independent front suspension, based on double transverse arms was constructed as an adaptation of passenger car suspension. During tests the suspension is blocked by removable bars. Blocking of the suspension ascertains proper leveling of the trailer. The test wheel is supported by a vertical arm (4) that is an important element of the force measuring system (Fig. 10.3).

The front and rear suspension are connected to the horizontal arm 1. Rotation axis 3 is placed directly in the geometrical centre of the rotation axis of the front wheels. The load is provided by arm 2 that has a common rotation axis with arm 1. The load block (6) is resting on arm 2.

Fig. 10.2: The tyre/road rolling resistance measurement trailer from TUG in the shape and condition of 2010.
Suspension element 7 carries the load from arm 2 to arm 1. The rear end of the horizontal arm 1 is connected to the vertical arm 4 which is equipped with the test wheel hub. Undesirable vibrations of the vertical arm 4 that may be induced during tests are suppressed by Foucault currents electromagnetic brake (not shown in the Fig. 10.3). Inflation pressure in the test wheel is maintained by remote controlled release valve and pressure sensor.

During tests the rolling resistance force acting on the test wheel pulls (deflects) the vertical arm 4. The deflection rate is measured by the laser sensor installed on arm 1 and sending the laser beam towards arm 4. Rolling resistance coefficient is defined as a ratio of rolling resistance force $P_r$ and vertical load $F_z$. The trailer is equipped with a patented compensation device that eliminates influence of factors such as road inclination and longitudinal acceleration that otherwise very substantially would disturb the measurements. The position of arm 1 in relation to the road surface is monitored by two laser sensors. A data logger (DaqBook/200) which is installed in the car receives signals form three laser sensors and two rotation sensors installed in the wheels. All measurements are controlled via a notebook computer (see Fig. 10.4).
The test wheel and the vertical arm, as well as the inclination compensation system are covered by an aerodynamic enclosure (Fig. 10.2). Both theoretical considerations and practical experience show that such an enclosure is necessary to reduce influence of the air drag on the test results.

During measurements the front suspension system is blocked by special bars to ascertain stable position of the trailer frame in relation to the plane of the road. Steel loads that load the test wheel are mounted on the arm (2 in Fig. 10.3) that has its own suspension based on a motorcycle spring and damper unit. This suspension unit is in operation both during transportation and testing.

10.3 The TUG measurement method
Before each measuring session the trailer is calibrated in the laboratory on a flat, horizontal surface.

During the measurements the test tyres are in warmed-up condition (warmed-up at least for 15 minutes, but always long enough to stabilize the inflation pressure). When the tyre is warm to allow testing the pressure is regulated.

At least two tests runs at each speed are performed. When possible the number of runs is higher and the runs are made in both road directions. Generally, a measurement distance per run of 400 m or more is required, but measurements over distances as short as 100 m are sometimes performed. Short distances require more runs in order to maintain an acceptable uncertainty. The longitudinal resolution is high and repeatability is excellent, see Fig. 10.5, but limitations are made by the very high variations that occur in the longitudinal direction, the most of which are averaged out by the data processing software.

The data are analyzed in laboratory.

![Graph](image-url)

Fig. 10.5: Illustration of repeatability of measurements. The trailer was run two times on a Swedish SMA surface, for two different tyres (W6c and W3c), starting measurements at the same position (within approx. 1 m) and running at the same speed (50 km/h, approx. 14 m/s). It means that on the horizontal scale, 1000 ms corresponds to approx. 14 m and that this entire measurement covered a distance of approx. 40 m (equal to 20 tyre revolutions).
10.4 The BRRC trailer

In 2009 BRRC decided to continue research started in the early 1980's and refurbished the original trailer. New sensors were added and calibration procedures were tweaked. Fig. 10.6 shows the new trailer and its towing car.

Fig. 10.6: The new BRRC trailer and its towing car.

The BRRC trailer is designed as a quarter-car with an ordinary car suspension. The suspension dates from the 1980's and was originally designed for a small car. Technological developments over the last years lead to larger tyres and heavier vehicles. As the trailer of BRRC was originally designed for tyres and cars commonly used in the 1980's, it now encounters some limitations. Only tyres with a maximum diameter of 14 inches and a maximum width of 195 mm can be mounted. A maximum load of 2000 N is imposed in order not to force the suspension system.

In 2011 a new tyre was mounted on the trailer: Michelin Energy Saver 195/70 R14 91T (see Fig. 10.7). Until then a slick tyre had been used: Michelin SB-15/63-14X (see Fig. 10.7). A tyre inflation pressure of 2.0 bar was used for the old tyre, while for the new test tyre a pressure of 2.2 bar is used.

Fig. 10.7: The new BRRC test tyre on the left (Michelin Energy Saver) and the old test tyre (Michelin SB) on the right.
The measuring principle is shown in Fig. 10.1. The rolling resistance force causes the wheel to incline backwards with an angle \( \theta \) with respect to the frame of the trailer. The rolling resistance coefficient is defined as the ratio of the rolling resistance force and the load on the wheel and equals the tangent of \( \theta \). For small angles, \( \theta \) is equal to the rolling resistance coefficient provided it is expressed in radians. A symmetric, friction-free pneumatic damper of bellows damps fluctuations of \( \theta \).

The trailer presently has no enclosure that can prevent the tyre air drag from affecting the results. This has the result that speed influences the measured results; i.e. the measured RR is higher for higher speeds.

Different parameters are registered continuously during measurement:

- Inclination \( \theta \) of the wheel carrier with respect to the frame of the trailer (Fig. 10.8)
- Inclination \( \mu \) of the frame of the trailer with respect to the horizontal plane (Fig. 10.8)
- Inclination \( \alpha \) between the trailer and the towing vehicle (Fig. 10.8)
- Tyre temperature: an external infrared sensor is directed at the sidewall near the shoulders of the tyre.
- Speed
- Acceleration

![Fig. 10.8: The BRRC rolling resistance test trailer and illustration of the three inclination angles measured.](image)

A software tool for data acquisition has been developed in LabVIEW. During monitoring the graphs of the different parameters are shown on the laptop screen. In this way the operator may be notified of possible errors during measurement. All data are registered in a file. Corrections are applied afterwards following this formula:

\[
C_r = \theta + \varepsilon_1 \times \mu + \varepsilon_2 \times \alpha
\]

where \( \varepsilon_1 \) and \( \varepsilon_2 \) are experimentally determined coefficients. So far, only a correction of the inclination \( \alpha_0 \) at standstill has been applied and measurements have been performed only at constant speed.
10.5 The BRRC measurement method
In general, the following measurement procedure is applied:
- Cold tyre inflation is adjusted to 2.2 bar.
- The height of the trailer with respect to the towing vehicle is measured to determine $\alpha_0$ at standstill.
- A calibration round is made to adjust $\mu_0$ and to eliminate the influence of differences in the car load (e.g. by a different number of passengers).
- A test tyre warm-up procedure is carried out, consisting of driving about 15 minutes at approximately 80 km/h.
- The test section is measured three times.
- Ambient air and road surface temperature are measured.
- Corrections of the data are applied in the laboratory using an excel sheet.
- Data are corrected for tyre temperature following this formula [Descornet, 1990]:
  \[ C_r(T) = C_r(T_0) * e^{(T_0 - T) / T_1} \]
  where $T = 30$ °C, $T_1 = 50$ °C
- Average RRC and corresponding standard deviation are calculated.

10.6 The BASt trailer
The BASt rolling resistance trailer for passenger car tyres applies a separate wheel suspension for the test tyre/wheel combination (see Fig. 10.9-10.11). This wheel suspension is mounted in the same geometric axis as the supporting tyres of the two-wheeled trailer. For applying the desired tyre load a pneumatic cylinder in combination with a nitrogen reservoir is used.

The test tyre/wheel combination is joined at point "B" and "C" with five links (three transversal and two longitudinal links in a parallelogram alignment) to the trailer chassis with a camber angle of 0°. The lower longitudinal suspension link is equipped with a force transducer for the longitudinal force. The pressure accumulator based vertical force $F_Z$ is passed via a force transducer and a bearing towards point "C".

Fig. 10.9: The BASt rolling resistance trailer for car tyres.
Besides the two force transducers for vertical tyre load $F_Z$ and longitudinal force $F_X$ ($= F_{LU}$) the trailer is equipped with a temperature sensor (PT100) to measure the ambient air temperature either in an enclosure around the test tyre or outside of it, as well as an infrared temperature sensor to measure the tyre temperature at its shoulder. Since there is an unavoidable influence from $F_Z$ towards $F_X$ if the trailer chassis is not parallel to the road, it is necessary to measure the position of the trailer platform with two laser displacement sensors mounted in the front and rear.
10.7 The BASt measurement method

The method used is illustrated in Chapter 9.1.3 ("two point method"). The different tyre loads \( F_Z \text{ high} \) and \( F_Z \text{ low} \) are realised by a dual pressure control unit with adjustable pressure values. Two electro-pneumatic valves operate the pressure for the tyre load cylinder.

The signal from the force transducers for the forces \( F_x \) and \( F_z \) is sampled at a rate of 500 Hz and the speed and temperature signals are sampled at 5 Hz. The rolling resistance value \( RRC \) is calculated from the mean values of \( F_x \) and \( F_z \) at high and low load, so there is one single value for the whole test track length. It is assumed that the rolling resistance value does not change significantly along the test track.

The calibration of the trailer is somewhat different from the PFF. A so-called "static" calibration is done to

1. determine the influence on the longitudinal force caused by a false vertical position of the wheel suspension for a certain operating point (depending on tyre size)
2. determine the dependency of the difference in height (of the trailer chassis) on the longitudinal force

This calibration has to be redone for each tyre/wheel combination whenever there is a change in diameter.

10.7 The IPW truck trailer

Together with Forschungsvereinigung Automobiltechnik (FAT), BASt has launched a project "Rolling Resistance of Truck Tyres (towed axle’s tyres) with a Trailer Method", which has been carried out by IPW Automotive in Hanover [Bode, 2011]. The test set-up is described in the following.

The rolling resistance of four truck tyres is measured with a complete truck-trailer set-up. The sum of the rolling resistance of the four tyres is measured by a drawbar force transducer between truck and trailer. The trailer body is loaded with defined loads to 18 t, so that the front and rear axle loads are balanced at 9 t each. Other loads are possible. The trailer is towed by a truck, which drives at a constant speed of 15 km/h to avoid wind effects (aerodynamic resistances) on the measuring results. Tyre and ambient temperature are measured as well as wind speed.

The rolling resistance coefficient in [%] is calculated by dividing the drawbar force \( F_{x \text{ res}} \) by four and relating to a wheel loading force \( F_z \) of 45000 N. Note that the RRC of truck tyres are much lower than those of passenger car tyres; for example, the measured values are between 0.4 % and 0.5 % on smooth surfaces.

Figure 10.12 shows the truck-trailer measuring system.

At the present time only 385/65 R22.5 tyres (with two profile heights) have been tested, but other tyre sizes are possible to measure, if mounted on 22.5 inch rims.

The four trailer tyres are not covered to avoid air drag, but at speeds of 15 km/h this seems not to be necessary. Tests have been run on even testing grounds without any gradient. The trailer has air springs and at a test speed of 15 km/h and operation on even surfaces, the damping component is believed to be negligible. As with the other trailer methods, bearing losses, if significant, are included in the measured values. Brake losses are assumed to be negligible. Wheel adjustments such as toe-in are closely checked.

Figure 10.13 shows the drawbar measuring system for truck tyre rolling resistance measurements.
10.8 The IPW truck trailer measurement method

With the test set-up described above it is important to have a plane and even test ground which allows travelling at low speed (15 km/h) in both directions, to eliminate the influence of gradients and cross winds. The values of the rolling resistance measurements from both directions have to be averaged. With such requirements the truck trailer method can only be used on local roads which have equal pavements in both directions (and no disturbance of traffic) or on special testing grounds. Highway measurements cannot be undertaken.

To warm up the tyre, a warm-up time before the measurement of rolling resistance can be started is specified by ISO to be 3 hours. This can easily be done by towing the trailer over this time period before measurement. By the warming up process the tyre pressure is increased and stabilized at a normal operating level. A higher inflation pressure leads to lower rolling resistance values, in general.
10.9 The Mobile Tyre Test Rig at ika / RWTH Aachen University

Due to a lot of discussions in the past about the pros and cons of either drum or flat belt tyre test rigs, a mobile test trailer has been developed and manufactured at the Institut für Kraftfahrzeuge (ika), RWTH Aachen University. See Fig. 10.14. This trailer is currently under construction but will start regular operation in the summer of 2011.

![The Mobile Tyre Test Rig at ika / RWTH Aachen University](image)

**Fig. 10.14:** The Mobile Tyre Test Rig at ika / RWTH Aachen University. Photo by courtesy of [Bachmann, 2011].

The main purpose with the trailer is to measure forces and moments of the tyre under real operation conditions. In order to compare these real road measurements from any public road or proving ground with laboratory measurements (Fig. 10.15), the trailer can also be positioned on a 2.54 diameter m outer drum, coated with a P80-corundum (3M "safety walk") sand paper surface (see Section 9.7, and Fig. 10.16). Within the laboratory it is much easier to reproduce and repeat measurements free from many of the other influences. A final target of the investigations of ika on the tyres is a kind of conversion map to transform laboratory measurements to user-defined test tracks by certain additional real road measurements.

The trailer is able to measure all types of tyres between 600 mm and 1300 mm diameter. The tyres are fixed to a strain gauges based measuring hub which is mounted in the centre of the wheel carrier. All necessary parameters like camber and side slip angles and vertical as well as horizontal travel distances can be measured and controlled by the central control unit. Thus, side slip angle, camber angle, wheel load, wheel speed, inflation pressure etc. can be adjusted dynamically to the test tyre. In addition to that an IMU-GPS VBox tracks the movements and angular changes of the wheel carrier, a Correvit optical speed sensor measures the longitudinal and lateral speed of the trailer as well as a rotational speed sensor measures the test tyre speed. Laser sensors measure the distance between wheel centre and ground, and several temperature sensors can measure the tyre, road and ambient temperatures.
The measuring hub is capable of measuring wheel loads up to 60 kN (Fx and Fy up to 50 kN). A hydraulic wheel load control in combination with four air bellow springs shall decouple any trailer movements from the test tyre as much as possible to maintain a constant wheel load. The necessary power (hydraulic, electric and pneumatic) is taken from a 27 kW diesel power pack which is mounted on the rear end of the trailer.

Depending on the tractor the test rig can run 5-100 km/h. Both rear axles of the trailer can be steered in order to compensate any side slip angles of the trailer which might occur from the lateral forces of the test wheel.

A disc brake on the measuring hub will allow brake slip up to 100 % so that also tyre/road friction can be measured at an arbitrary slip.

Regarding rolling resistance measurements the test rig can be calibrated on the drum mentioned above by an external torque sensor in the drum drive shaft ("torque method"). Then the complete truck can repeat measurements on a test track. Here both Fx and Fz are measured in the hub as well as the position (inclination angles) of the wheel carrier.

Warm-up of the tyres can be done either on a drum or by driving on a real road.

An additional housing of the tyre could easily be adapted to the wheel carrier to avoid disturbing wind and air drag influences on the RR measurements.

This section is adapted from a text supplied by Mr Christian Bachmann at RWTH in Aachen, who has also kindly supplied the photos [Bachmann, 2011].
11 MEASUREMENT METHODS – COASTDOWN METHOD

11.1 Historical remarks
Coastdown measurements were done as early as in the 1920’s to investigate the influence of different road pavements on rolling resistance [Agg, 1928]. Another early equipment was the tricycle vehicle in Fig. 11.2 that was constructed and used by VTI in 1980 for testing RR of bicycle tyres. This vehicle was placed on a ramp from which it was released and the coastdown over a long workshop floor was recorded [Arnberg et al, 1980].

Fig. 11.1: Precision equipment "Ames Space-time Recorder" for measuring retardation (speed) during coastdown, as used by [Agg, 1928].

Fig. 11.2: Tricycle for testing RR of bicycle tyres at VTI [Arnberg et al, 1980]. The device was placed on a ramp, released and RRC was calculated from the coastdown.

11.2 Basic idea
Suppose that a specific road section with well-defined start and end points is given. A coastdown measurement on this road section is performed by letting the vehicle roll freely (clutch down, gear in neutral position) between the start and end points. The velocity is measured7 "continuously" along the road strip, see example in Fig. 11.3. The acceleration is either measured directly or is derived from the velocity curves.

The various resistive forces acting on the vehicle will make it slow down. The rolling resistance is one of these forces. The larger the rolling resistance the larger the retardation becomes. By performing several coastdown measurements, under various conditions, it is possible to distinguish and separate the contributions of the different resistances acting on the vehicle. In particular, if the measurements are performed on different roads with varying road surface properties, it is possible to infer how the rolling resistance depends on the road surface variables.

7 A possible alternative could be to measure the velocity only at the start and end points. This would imply a somewhat different analysis method than has been used in this project.
Fig. 11.3: Velocity curves for several coastdowns with varying initial velocities along one particular road strip. The curves are almost parallel which indicates that the measurement conditions have been similar. To the right, the acceleration curve for one specific coastdown. Typically, strong fluctuations occur, caused by small measurement errors.

It is of fundamental importance that other forces acting on the vehicle (especially gravitational forces and air resistance) are eliminated in the computations. This can be done either explicitly by direct measurements or indirectly during computations.

11.3 Characteristic features of the method

A major advantage of the coastdown method is that it is easily applied to any vehicle without much equipment. For instance, it can be applied to heavy goods vehicles (HGV:s), with or without trailers, as well as for bicycles, in the same way as for private cars. Essentially, the only quantities needed are the vehicle’s position and velocity (or acceleration).

Another feature of the method is that measurements are performed for an entire vehicle in motion. This means that all resistive forces are included in the measurements. On the one hand this can be regarded as an advantage since this will guarantee that no effect is missing. For instance, the resistive force generated by road unevenness or by the side forces acting on the vehicle will be included in the total effect. On the other hand this can also be regarded as a disadvantage, since a number of resistive forces (most notably the gravitational force and the air resistance) have to be subtracted from the total force in order to obtain the RR. Much of the difficulties in applying the method consists in eliminating (or compensating for) these other effects.

Of particular importance in this context is the transmission resistance, essentially due to rotating axles and gear wheels in oil (especially in the rear gear). This effect is far from negligible and can be in the order of 50-60 N for a private vehicle (as compared to maybe 170 N for the RR). In principle, particular coastdown measurements can be used for isolating the transmission resistance (by varying the load on the vehicle), but experiments have shown that in practice it is difficult to do this with sufficient precision. The transmission resistance might however be estimated by other methods8.

---

8 A more extreme alternative, as is used in [Agg, 1928], is to detach the transmission altogether and let the vehicle be towed by another vehicle until the coastdown starts.
Another characteristic feature for coastdown methods is that the velocity varies during a coastdown measurement. Thus, coastdown measurements cannot be performed at a specific, constant velocity, which is typically done in trailer or drum measurements. Instead, variation of RR with velocity is an intrinsic part in the analyses.

11.4 Mathematical models
The coastdown method requires that models for each type of forces involved are mathematically formulated. In this section, examples of such models are described.

11.4.1 Model assumptions
The basis for a mathematical model for coastdown is Newton’s second law. The total force acting on the vehicle is the sum of the gravitational force and the drag force, where the drag force can be assumed to consist of: rolling resistance, air resistance, side forces resistance, transmission resistance and gravitational resistance.

\[ -M_e \dot{\theta} = F_{\text{side}} + F_{\text{air}} + F_{\text{side}} + F_{\text{trans}} + F_{\text{grav}} \]  \hspace{1cm} (1)

The various forces are supposed to depend on the following variables:

- **Gravitation force:** \( F_{\text{grav}} = mg \sin(\theta) \)
- **Side force resistance:** \( F_{\text{side}} = F_{\text{side}}(v, m, R, \theta, \sigma) \)
- **Transmission resistance:** \( F_{\text{trans}} = F_{\text{trans}}(v) \)
- **Rolling resistance:** \( F_{RR} = F_{RR}(v, m, T, IRI, MPD) \)
- **Air resistance:** \( F_{\text{air}} = F_{\text{air}}(v, A, \rho, w, \alpha) \)

Where

- \( m \) is the mass of the vehicle
- \( M_e \) is the inertial mass
- \( g \) is the standard value of gravitational acceleration
- \( \theta \) is the longitudinal slope of the road
- \( v \) is the speed of the vehicle
- \( R \) is the radius of curvature of the road
- \( \sigma \) is the crossfall of the road
- \( T \) is ambient temperature
- \( IRI \) is the IRI measure of road unevenness
- \( MPD \) is the mean profile depth measure for macrotexture (ISO 13473-1)
- \( A \) is the cross-sectional area of the vehicle
- \( \rho \) is the density of air
- \( p \) is the air pressure
- \( w \) is wind speed
- \( \alpha \) is wind direction (relative to the velocity vector of the vehicle)

\( C_{\text{side}}, C_{d0}, C_{d1}, C_{r00}, C_{r TMP}, C_{r MPD}, C_{r IRI}, C_{r IRIV} \) are constant coefficients

In more detail:

\[ F_{\text{side}} = C_{\text{side}} \cdot F_{y}^{2} \]

\[ F_{y} = m^{*}(\cos(\sigma)^{*}v^{2}/R-g^{*}\sin(\sigma)^{*}\cos(\theta)) \]
For the rolling resistance the following model might be appropriate:

\[ F_{RR} = mg(Cr_{00} + Cr_{MPD} \cdot T + Cr_{IRI} \cdot IRI + Cr_{IRIv} \cdot IRI \cdot v) \]

The transmission resistance can be modelled as a constant term (independent of the mass of the vehicle), although it should rather depend on the vehicle speed.

\[ F_{trm} = C_{trm} \]

### 11.4.2 Equations

Combining the equations in the previous section yields this general equation (in differential form):

\[
-M_e \frac{dv}{dt} - F_z \cdot \sin \theta = C_{trm} + F_z \cdot \left(Cr_{00} + Cr_{mp} \cdot T + Cr_{MPD} \cdot MPD + Cr_{IRI} \cdot IRI + Cr_{IRIv} \cdot IRI \cdot v\right) + C_{side} \cdot F_y^2 + F_{air}
\]

where \( F_z = mg \).

One can also formally integrate this expression with respect to time or position. This yields a possibility to formulate equations in terms essential of quantities at the start and end points and mean values over the strip.

### 11.4.3 A variety of possibilities

The goal is to determine the coefficients \( Cr_{00}, Cr_{MPD} \) etc. There exists a large number of possibilities to do this. First of all, there are variations in the formulations of the models in section 11.4.1 (in particular the air resistance and the rolling resistance). Secondly, the level of aggregation, e.g. choosing between a differential or an integral formulation, also might affect results although the mathematical expressions are equivalent. Thirdly, there exists a variety of choices of numerical schemes for calculating the coefficients.

It is reasonable to assume that the differential formulation is advantageous whenever all data available is of high quality, since it contains more information than the integral expression. On the other hand, if some of the data are of lesser quality, then the integral approach might be advantageous, since these expressions are less vulnerable to disturbances. Aggregation can also be done on data from the differential formulation. The effect of this type of aggregation is probably similar to the integral formulation.

Applying the equations to data yields an over-determined equation system from which the coefficients can be computed by for example a least squares method (regression). For the differential approach this can be done on one single coastdown at a time or on the entire set of data.

### 11.5 Measurement setup in MIRIAM

In this section we propose a setup for the coastdown measurements to be done in Miriam.

#### 11.5.1 Selection of test roads

A number of different test roads must be selected. These should have very differing macrotexture and unevenness. It is important that macrotexture and unevenness do not correlate.
too strongly. Also, it is advantageous if road surface conditions do not vary much across the road. A good balance between different MPD values is desired, as is the case for IRI.

If coastdowns are measured with GPS equipment, the test roads should not be bordered by large buildings or trees obstructing the GPS signals. It should also be free from curves and preferably not too much slope.

### 11.5.2 Road data measurements

Road surface data is measured using a road surface tester (RST) from VTI, see Fig. 7.1. Road surface quantities should preferably be measured for each meter for both wheel tracks. Besides the usual road surface quantities, also the road longitudinal profile should be measured if other indicators for macro- or megatexture or unevenness will be analyzed.

Slope should be measured with high precision. The difference in altitude between start and end points of each test road must be determined with particular precision (maximum a few cm of uncertainty).

### 11.5.3 Measurement equipment for coastdowns

**Coastdown logging:**

It is appropriate to use GPS equipment for measuring the velocity. VBOX 3i from Racelogic has been used in earlier projects with good results (Fig. 11.4). VBOX measures speed and distance with a frequency of 100 Hz. Measurements are based on the Doppler effect, which means that speed (not position!) is the primary quantity being measured. In situations where the signals from satellites are of less quality (for short time periods), VBOX uses accelerometers to interpolate and improve the speed curve.

The equipment includes an antenna which should be mounted on the top of the vehicle. VBOX needs a power supply, for example the cigarette socket in the car, or better, an extra car battery.

![The VBOX GPS unit](image)

**Fig. 11.4:** The VBOX GPS unit.
Device to detect start and end points of a test road:

It is desirable to record the precise time point when the vehicle is passing the start and end points of the road strip. This will eliminate any uncertainties concerning the vehicle's position during the coastdown. The position provided by the GPS is not considered to be of sufficient precision. Reflectors are positioned at the road side at start and end points of the road. On the right side of the vehicle an optical sensor is mounted, which registers the time point when the sensor passes the reflector. This registration is merged together with the VBOX GPS data.

Weather station:

A weather station measuring wind speed, wind direction, air temperature, air pressure and humidity, is positioned at a suitable location beside the road. Registrations should be done at least once per minute. Road temperature is measured at stationary stations, which might be located rather distant from the road strips.

Tyre pressure and temperature:

In previous RR projects carried out at VTI, measurements of tyre pressure (and adjustments) and temperature have been done manually when arriving at a test road. For an HGV, tyre pressure is measured (and adjusted) once per day, in the morning before the coastdown measurements start.

The procedure for measuring (or controlling) wind speed, temperature and tyre pressure is a subject of much discussion at VTI. Efforts for improving the suggested procedure should be made.

11.5.4 Coastdown measurements

First a series of coastdown measurements should be done investigating the influence of

- Air (and road) temperature
- Wheel temperature
- Tyre pressure
- Meteorological wind
For each of these variables the range of values should be large, while all other variables should be kept as constant as possible. In particular, one and the same test road should be used.

Then, measurements for various road strips can begin. At a specific road strip, at least three (but preferably more, maybe seven) coastdown runs should be done in both directions. The initial velocity should vary from one run to another, e.g., 90, 70, 50, 80, 50, 70, 90 km/h.

11.5.5 Data analyses
It is important to “clean” data from obvious measurement errors. A first check is done by simply plotting the velocity curves as function of position. A comparison between all curves in one test road and direction immediately reveals any deviating coastdown.

The number of satellites in contact should not be lower than a minimum value. Integration of the velocity curve with respect to position should approximately yield the total distance of the test road.

11.6 Difficulties and problems
A drawback with the coastdown method is that it is vulnerable to a large number of potential error sources. Each of these has to be controlled so as to minimize the total error. In this section the most serious error sources are highlighted. Also some other difficulties concerning the design of measurements and analyses are discussed.

1. Which explanatory variables to include in the model and how to record them with good accuracy?
2. How to model RR as a function of, for instance, the temperature? Besides IRI, a number of different alternative measures for “unevenness” exist. Likewise for the macrotexture. Also, megatexture might be included as an explanatory variable? Linear or non-linear relationships? Different models for driving wheels and freely rolling wheels? The rolling resistance coefficient might be changing by tyre load.
3. How to avoid correlations between road surface variables? Since we wish to express RR in terms of both macrotexture (MPD) and road unevenness (IRI) it is of particular importance to avoid correlations among these two quantities. Special care must be exercised when selecting the road strips on which the coastdowns will be performed so that correlations are kept to a minimum. One might also expect correlations between explanatory variables to depend on the interval length of road descriptions.
4. How to avoid correlations between road surface variables? If measurements along different road strips (with different road surface characteristics) are carried out during different meteorological conditions and these conditions are not properly compensated for, then correlations between any of the road surface variables and, for instance, the temperature may occur. This might decrease the precision in the results.
5. Variation by time of ambient temperature and air pressure influence tyre pressure. Increasing tyre pressure reduces rolling resistance. The tyre pressure is affected by:
   a. the air pressure: increasing air pressure will decrease the tyre pressure
   b. the air temperature: increasing air temperature will increase the tyre pressure
   c. the tyre work: increasing work will increase the tyre temperature and the tyre pressure. This includes also the speed of the vehicle.
   d. the load of the vehicle.
   These changes will be expected if there are no adjustments of the tyre pressure. Tyre temperature is not only of importance for tyre pressure but also directly for driving resistance. The temperature of the material in the tyre will influence rolling resistance.

How to handle tyre air leakage and how to do the adjustments?
6. How to handle the influence of wind?

7. **Variation in road surface conditions across the road.** Even if one uses standardized measures for road surface conditions with high degree of explanation for driving resistance, problems can follow from the variation in conditions across the road. The impact of road surface conditions on the motion of the vehicle will depend on the side position of the vehicle and the width between the wheels on the left and right side of the vehicle. For heavy vehicles with four wheels on the rear axle there will be a difference between road condition exposure for the wheels on the front and rear axle. If rolling resistance effects are estimated based on measurements in an ideal situation the side location for each wheel and the road conditions in these positions should be known along the test route. In practice this will be difficult to fulfil. We believe that this is a serious threat to precision in the results.

8. **Changes in the test vehicle weight during a day and between days.** The vehicle should have as constant weight as possible. Or at least, one should keep track of any changes of the vehicle weight, e.g., the amount of fuel in the vehicle and the weight of the driver.

9. **How to determine when the vehicle is fully warmed up?** Not only the tyres but also the transmission etc. needs to warm up.

10. **Separation between RR and transmission losses.** The transmission resistance includes two parts: mechanical losses between the gear-wheels and oil churning losses. During coastdown with the gear box in neutral position there is essentially one part present: the oil churning losses. The rolling resistance increases with increasing vehicle weight and the oil churning losses are independent of vehicle weight. By varying the vehicle weight it should be possible to separate rolling resistance and transmission resistance. However, it is difficult to do this with acceptable precision.

### 11.7 Other coastdown equipment

A special coastdown method is sometimes used at Nokian Tyres in Finland. As shown in Fig. 11.6, a car equipped with the tyres under test is placed on a ramp in a workshop or storage building having a very long concrete floor. At a given instance, the car is released and rolls down the ramp and continues to roll along the workshop corridor. The distance rolled until it stops is a relative measure of the rolling resistance [Liukkula, 2010]. It is unknown to the authors whether the method is used for any other purpose than demonstration.

Fig. 11.6: Coastdown method at Nokian Tyres in Finland, with a car with test tyres rolling down a ramp and the coasted distance taken as a relative RR measure [Liukkula, 2010].
12 MEASUREMENT METHODS – FUEL CONSUMPTION METHOD

No partner in MIRIAM is currently using this method. However, in the past it has been used by VTI a number of times [Sandberg, 1990] [Jonsson & Hultqvist, 2009]. There are no plans to use it again in MIRIAM. For this reason the fuel consumption (FC) method is not described in this report.
13 MEASUREMENT METHODS – REFERENCE TYRES

13.1 Desired and actual properties

When classifying or ranking pavement properties for rolling resistance it is necessary to use reference tyres. The purpose of the tyres is to be representative of the category of tyres that they are intended to represent and to provide stable and repeatable conditions. A common reference tyre concept is that one tyre shall represent the fleet of car tyres on the roads (tyre category C1), and another tyre shall represent the fleet of truck tyres (C3). One might also want to have a tyre representing the middle range; van tyres (C2). Reference tyres must be available for a long time.

This concept is already implemented in the drafts ISO 11819-2 and ISO 11819-3 which are two documents specifying the so-called CPX method for classification of noise properties of pavements. The tyres used in the CPX method are shown in Fig. 13.1.

![Fig. 13.1: Reference tyres specified for the CPX method (ISO 11819-2 and 11819-3). The tyre at the right is an extra tyre used by TUG from the time when they started to make RR measurements, and has been kept for the purpose of providing a link to old measurements.](image)

The SRTT (“Standard Reference Test Tire”) is a tyre specified in ASTM F2393 as a reference tyre for various purposes. The Avon AV4 tyre is a tyre tested and found to classify pavements (for noise) in roughly the same way as a selection of regular heavy truck tyres do. It is in fact a light truck tyre, but as the smallest dimension for this series of tyres is used, the AV4 fits on large passenger cars, as does the SRTT.

The SRTT and the AV4 are tyres considered to become reference tyres also for rolling resistance, and will be tested for this purpose in MIRIAM.

As it is a reference tyre nominated by ASTM, the SRTT is likely to be available for several decades in the future. The AV4 tyre will not be manufactured in the future unless the users of CPX tyres orders a full batch of 100 or more tyres simultaneously, which is the plan.

Another SRTT, having a tread pattern which could make it useful as a second reference tyre for rolling resistance, is presently being developed by Michelin and subject to standardization.
by ASTM. This tyre will not be available for testing by MIRIAM already from the start of the project, but may be of interest in a later phase. It would be interesting to test whether it could serve in the same way as Avon AV4 is hoped to serve, i.e. as a “proxy” for a truck tyre.

There are also a number of other reference tyres available for various purposes, almost entirely for the main purpose of measurement of wet skid resistance. Both ASTM and PIARC have several such tyres specified.

A special problem is that reference tyres are always used in new condition; when they get a little worn they are not considered as useful any more. However, tyres rolling on our roads are a mix of new, worn out and partly worn tyres. If we want to have representative reference tyres, there should also be some tyre that may represent worn tyres. This is still an unresolved problem.

13.2 Market tyres used as temporary references

Market tyres are not very suitable reference tyres as they are available only for a few years, and because they are often subject to small changes in the rubber compound despite maintaining the same brand and type name. Nevertheless as a temporary reference, one may want to use some reference tyres picked-out from the replacement tyre market.

One such example is the Michelin Primacy tyre shown in Fig. 13.1. Another example may be the Michelin Energy Saver (Fig. 10.7), which has already become a very popular tyre in a short time.
14 MEASUREMENT METHODS – REFERENCE SURFACES

14.1 General

Testing RR properties of road surfaces requires references tyres, but equally important is it to have reference road surfaces when testing RR properties of tyres. From the previous chapters it seems that there are five properties of road surfaces that affect the RR of tyres:

- road unevenness
- megatexture
- macrotexture
- microtexture
- stiffness

In order to measure the tyre's sensitivity to all these, one should ideally have one reference surface that highlights each special property.

As we still have too little information about the quantitative importance of microtexture, megatexture and stiffness, the authors think that one may wait to consider these. Therefore, with the current knowledge, it is recommended to focus on macrotexture and unevenness.

One option would be to use two surfaces as follows:

- Surface # 1 with low macrotexture and low unevenness, but not lower than typical of a high-quality road surface
- Surface # 2 with high macrotexture and high unevenness, but not higher than typical of a highway surface in poor condition

To find such surfaces on roads would not be so difficult; however, to standardize and specify such surfaces would require some substantial work. In the meantime, it should be a task in MIRIAM to work out some recommendations for temporary references according to this concept.

It should be noticed that the ISO 10844 is the only existing specification for a reference road surface, and this one may be a good candidate for surface # 1 above. Fig. 14.1 illustrates such a surface.

Fig. 14.1: A test track surface satisfying the requirements of ISO 10844; located at the BASt research centre.
14.2 ISO laboratory drum surfaces

The present standards require the use of laboratory drum facilities. But these drums are allowed to use either smooth steel or smooth sandpaper surfaces. None of them is even close to resemble anything we can accept to have on actual roads. They should be replaced with replicas of real road surfaces. Such can be made just as TUG and BASt make and use such drum surfaces today. There are several tyre and vehicle manufacturers as well as other laboratories worldwide which have such surfaces on drums already, but for use when making noise testing of tyres. It would be no big difficulty of employing the same technology for rolling resistance drums. Fig. 9.8 shows such surfaces already existing on the 2.0 m drum for RR measurement at TUG.
15 CORRELATION BETWEEN MEASUREMENT METHODS AND EQUIPMENT

15.1 The laboratory drum methods
A 2003 study by Ecos Consulting sponsored by California Energy Commission (CEC) evaluated both SAE J1269 and SAE J2452 for rolling resistance testing, and recommended that use of SAE J2452 would be more advantageous [Tiax, 2003]. Three reasons were provided:

1. major tyre manufactures currently have the ability and facility to perform SAE J2452 tests;
2. several auto manufacturers have also requested SAE J2452 data to improve calculation of vehicle fuel economy
3. SAE J2452 represents a more complete, sophisticated level of testing as well as a more complete picture of rolling resistance than SAE J1269.

The report also estimated the cost of performing SAE J2452, which consists of an approximately $200,000 investment for testing equipment and $300 to $500 per-tire test.

In 2009, the U.S. Department of Transportation/NHTSA conducted a study evaluating different test standards and examining the correlations between the results from different standards [Evans et al, 2009]; this is the only study to date focused on the quantification of the correlation between test methods in the U.S. This study showed that results from all of the rolling resistance test standards could be cross-correlated, thus essentially providing the equivalent information about individual tyre types. Analysis of variance (ANOVA) showed that among the results, “test method” is not a statistically significant parameter compared to “individual tyre.” This study also showed that different laboratories could produce significant discrepancies on the test results.

In order to compare the results, a method to address these discrepancies between laboratories was necessary and also practicable. The study identified two methods:

1. using lab-to-lab correlation equations, based on a reference laboratory
2. using a Standard Reference Test Tire (SRTT) to normalize data across labs

Based on the findings, this study recommended using ISO 28580 as the rolling resistance test. The report reasoned that although a multi-point test is necessary to characterize tyre rolling resistance over a range of loads and pressures, the single point test is simple to perform, provides sufficient information to assess and rate individual tyres in a common system, and already has a laboratory alignment procedure in it. This would be particularly advantageous considering the large number of tyres that these experiments usually involve. It was also noted in the study that the European Commission has selected this standard as its basis for the rolling resistance rating system, so its use would allow comparison across U.S. and European tests.

15.2 The trailer and drum methods
A few measurements have been made with the same tyres on the TUG drum and on the TUG trailer. Such a measurement is shown in Fig. 15.1. Note that the road (SMA 0/16) had a considerable roughness (in the megatexture and unevenness range, something that did not exist at all on the drum).

It appears that the ranking of the tyres is quite different with these methods. It is believed that the main reason is that the drum surface texture is very far from the road surface.
15.3 Comparison of RR measuring equipment in the IPG project

As part of the huge Dutch IPG research program\(^9\) a pilot study was carried out to perform a round robin test (RRT) of measurement systems for determining the rolling resistance of road surfaces and the energy consumption of vehicles [Roovers et al, 2005]. The participants were M+P (noise consultant in the Netherlands), BASt, the Technical University of Gdansk (TUG), the Free University of Brussels (FUB) and the City of Rotterdam. BASt and TUG made measurements with their RR trailers, while M+P and the Free University of Brussels made measurements of energy consumption with test cars.

The trailers used the following two tyres for testing (one by one):

- Dunlop SP30, 175/65R14 82T
- Continental CPC2 LI98, 175/65R14 82T (this tyre has a tread but without any pattern)

The measurements were performed on 15 road surfaces in the Netherlands and Germany in November 2004. The speed on highways was 70 and/or 90 km/h for all devices. At the inner-city roads the speed was 50 and/or 70 km/h. The requirements on measured distance and number of runs were according to Table 15.1.

Table 15.1: Requirements on measured distance and number of runs [Roovers et al, 2005].

<table>
<thead>
<tr>
<th>Devices</th>
<th>Minimum total measurement length</th>
<th>Minimum number of runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling resistance by trailers</td>
<td>1.0 km</td>
<td>4</td>
</tr>
<tr>
<td>Energy consumption by cars</td>
<td>2.0 km</td>
<td>5</td>
</tr>
</tbody>
</table>

---

\(^9\) IPG = Innovatieprogramma Geluid, was a Dutch Noise Innovation Programme on noise mitigation with the objective of implementing a new set of measures for decreasing traffic noise near roads and railways. See [http://www.innovatieprogrammageluid.nl/](http://www.innovatieprogrammageluid.nl/)
Air temperatures varied between 8 and 12 °C during the tests. The measurement campaign was performed within three days. Not all measurement teams were able to measure all tracks completely according to plans.

It should be noted that when these measurements were conducted, both trailers were in a much less developed stage than they are at the present time.

First, Fig. 15.2 shows the RRC for all tested road sections and the two trailers and the two test tyres. The results of the comparison of trailers and of test tyres are shown in Figs. 15.3 and 15.3.

Fig. 15.2: Rolling resistance coefficient for all tested road sections (NL are roads in the Netherlands, the others are roads in Germany), for the two trailers and the two test tyres. By "profiled" tyre they mean a tyre with a normal tread pattern (Dunlop SP30). Test roads NL8, B1 and D1 were cement concrete pavements while the rest were bituminous pavements. From [Roovers et al, 2005].

Based on the repeatability and reproducibility data from the measurements with the BASt and TUG trailer systems, it was concluded that the applicability of the systems using a tyre with a normal tread was good for measuring differences in rolling resistance between pavements. However, the results were inconsistent in determining absolute values of rolling resistance. When using a tyre with slick tread (no pattern), also the RR differences between pavements were less reproducible.
Fig. 15.3: Rolling resistance coefficient measured by TUG as a function of the same measured by BAS. The left diagram is for the Dunlop SP30 which had a normal tread pattern, while the right diagram is for the Continental tyre which has a slick tread (no pattern). From [Roovers et al, 2005].

Fig. 15.4: Rolling resistance coefficient measured for the slick tyre as a function of the same measured for the patterned tyre. The left diagram is for the measurements by BAS, while the right diagram is for the measurements by TUG. From [Roovers et al, 2005].

A diesel fuel car and an electric car were included in the study to provide an alternative way of (indirectly) measuring the rolling resistance properties, and to estimate the driving energy differences (which are due to rolling resistance differences) between the pavements.

The results for the two cars are shown in Figs. 15.5 and 15.6.
Fig. 15.5: Diesel fuel and energy consumption for all tested road sections (NL are roads in the Netherlands, the others are roads in Germany), for the two cars. From [Roovers et al, 2005].

Fig. 15.6: Diesel fuel consumption versus energy consumption for the tested road sections. From [Roovers et al, 2005].
It was found that the two cars provided measurement results which were in poor correlation with each other. Therefore, it was concluded that the applicability of the systems for measuring differences in energy consumption was poor, as the measurements appeared to be too much influenced by external parameters.

The rolling resistance measurements with trailers showed no correlation with the electric energy consumption measurements or with the diesel fuel consumption measurements; see Fig. 15.7. One of the reasons for this was believed to be that the measurement results were strongly influenced by wind conditions (mainly for the cars).

![Fig. 15.7: Diesel fuel consumption versus rolling resistance coefficient measured with the BAStr trailer using the Dunlop SP30 tyre (left part of the figure), and electric energy consumption versus rolling resistance coefficient measured with the BAStr trailer using the Dunlop SP30 tyre (right part of the figure). From [Roovers et al, 2005].](image-url)

### 15.4 Planned round robin test (RRT) in the MIRIAM project

It is planned to conduct a round robin test (RRT) in MIRIAM in the summer of 2011, to be performed essentially at the test tracks of IFSTTAR in Nantes, France. In this experiment the three trailer systems (BAStr, BRRC and TUG) as well as coastdown vehicles from VTI are planned to take part, plus comprehensive measurements of the test track geometrical and other surface properties.
16 LEGISLATION AND OFFICIAL REQUIREMENTS

In 2009, two EU Regulations were issued which have a bearing on MIRIAM; a regulation on maximum limits for tyres and a regulation on labelling of tyres; both of them including requirements with regard to rolling resistance [EC 661, 2009][EC 1222, 2009].

Regulation (EC) 661/2009 includes requirements on new tyres sold in the EU as follows:

- Maximum limits for noise level
- Maximum limits for wet skid resistance (truck tyres excluded)
- Maximum limits for rolling resistance
- Requirement to use a tyre pressure monitoring system (TPMS)

The rolling resistance is to be measured in accordance with ISO 28580 and the limits are shown in Table 17.1 for the various categories of tyres. UN ECE Regulation R117 includes similar requirements on rolling resistance.

Table 17.1: Maximum allowed rolling resistance coefficient, expressed in kg/tonne, which is the same as the unitless RRC, multiplied with 1000. Tyre class C1 is passenger car tyres, C2 is van tyres and C3 is heavy vehicle tyres. For "snow" tyres, the limits in the table shall be increased by 1 kg/tonne.

<table>
<thead>
<tr>
<th>Tyre class</th>
<th>Max value (kg/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>12,0</td>
</tr>
<tr>
<td>C2</td>
<td>10,5</td>
</tr>
<tr>
<td>C3</td>
<td>8,0</td>
</tr>
</tbody>
</table>

The other one is Regulation (EC) 1222/2009 which includes requirements of labelling tyres with respect to:

- Noise level
- Wet skid resistance (truck tyres excluded)
- Energy efficiency (in practice, the parameter is rolling resistance)

The labelling shall be implemented on new tyres sold from 1 Nov. 2012. Yet, it is expressed in the regulation that "Tyre suppliers and distributors should be encouraged to comply with
the provisions of this Regulation before 2012”. The label shall look according to Fig. 17.1 and the energy efficiency classes are defined in Table 17.3. Testing shall be made according to ISO 28580.

Table 17.3: The "energy efficiency classes" A,B,C,D,E,F,G and the corresponding limits for rolling resistance coefficient (RRC), according to Regulation EC 1222/2009.

<table>
<thead>
<tr>
<th>C1 tyres</th>
<th>C2 tyres</th>
<th>C3 tyres</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRC ≤ 6.5</td>
<td>A</td>
<td>RRC ≤ 5.5</td>
</tr>
<tr>
<td>6.6 ≤ RRC ≤ 7.7</td>
<td>B</td>
<td>5.6 ≤ RRC ≤ 6.7</td>
</tr>
<tr>
<td>7.8 ≤ RRC ≤ 9.0</td>
<td>C</td>
<td>6.8 ≤ RRC ≤ 8.0</td>
</tr>
<tr>
<td>Empty</td>
<td>D</td>
<td>Empty</td>
</tr>
<tr>
<td>9.1 ≤ RRC ≤ 10.5</td>
<td>E</td>
<td>8.1 ≤ RRC ≤ 9.2</td>
</tr>
<tr>
<td>10.6 ≤ RRC ≤ 12.0</td>
<td>F</td>
<td>9.3 ≤ RRC ≤ 10.5</td>
</tr>
<tr>
<td>RRC ≥ 12.1</td>
<td>G</td>
<td>RRC ≥ 10.6</td>
</tr>
</tbody>
</table>

Figure 17.1: Label for tyres required in Regulation EC 1222/2009. The one on the top left is for "fuel efficiency"; i.e., rolling resistance.
17 ROLLING RESISTANCE ISSUES OF INTEREST IN FURTHER MIRIAM WORK

In order to get a good understanding of the phenomena associated with the subject “Rolling resistance”, especially in view of a model that calculates the energy and environmental effects of rolling resistance, there is a large number of issues that need to be studied. Some of them have already been covered in research projects in the past and knowledge about them is fairly good, some have been studied but much more work is needed, and some are practically virgin topics to explore. The following is a non-exhaustive list of such issues, as identified by the authors and categorized into a few main topics:

Tyre-vehicle interactions

- influence on RR of wheel bearing friction
- influence on RR of the transmission
- influence on RR of air resistance of the rim
- influence on RR of the side force (horizontal radius and cross fall)
- influence on RR of a bogie in horizontal curves
- influence on RR of driven or braked versus free rolling tyres (torque)
- influence on RR of the wheel alignment (camber angle)

Tyre properties

- influence on RR of the tyre construction when driving on a smooth and plane surface
- influence on RR of studs in tyres
- influence on RR of different tyre dimensions
- influence on RR of tyre tread pattern
- influence on RR of tyre wear and condition

Pavement properties and conditions

- influence on RR of different road texture and unevenness wavelengths (which part of the spectrum has the highest influence on RR)
- influence on RR of different common road surface measures (IRI, MPD, megatexture)
- influence on RR of stick-slip motions
- influence on RR of road stiffness
- influence on RR of road wetness and water depth
- influence on RR of snow or ice on the road
- influence on RR of ruts in the road surface (see also side forces above)

Measurement problems

- influence on RR of rolling tyres on a curved versus a flat surface (lab drum curvature)
- influence on RR of wheel brakes, if not totally released
- influence on RR of selected tyre inflation
- influence on RR of resulting tyre pressure due to measuring conditions
- influence on RR of resulting tyre temperature due to measuring conditions
- influence on RR of tyre inflation gas (stability with time and temperature)
- influence on RR of ambient air temperature and pressure
- influence of ambient air temperature and air pressure on tyre temperature and inflation pressure
- influence of driving conditions on tyre temperature and inflation pressure
- influence of tyre load on tyre temperature and inflation pressure
the issues under "Tyre-vehicle interaction" above are also measurement problems and should be copied here

For SP 1 in MIRIAM, the most important items are those relating to pavement properties and conditions and measurement problems. Several of them have already been scheduled for experimental work in SP 1.

The situation is more complicated than apparent from the list above, since many of these variables interact with each other and these interactions need also be studied. In order to find solutions to all questions, an almost infinite number of measurements are needed. Waiting for the progress through continuous research on RR to solve these questions by and by, the remaining questions could perhaps be addressed based on qualified guesses by experts, where modelling or other work is in absolute need for the answers.

SP 1 in MIRIAM will supply input information for SP 2 in MIRIAM which deals with modelling of energy consumption and effects on environment, as a result of rolling resistance and its relation to pavement properties. A Deliverable of SP 2 is being produced simultaneously with this report, and the reader may want to follow-up this work in the SP 2 report [Haider et al, 2011]. Also the ECRPD report [ECRPD, 2010] and a French report are of special interest with respect to the modelling issues [Boujard, 2009].
18 CONCLUSIONS AND RECOMMENDATIONS

The following major conclusions are made:

1. Tyre RR test methods lack consideration of realistic road surfaces
2. Standard test methods are available only for testing tyre RR in laboratories (SAE and ISO methods)
3. Standard methods for testing RR related to road pavements must be developed
4. Road parameters that clearly affect RR include macrotexture (represented by MPD), megatexture, and unevenness (represented by IRI).
5. There are indications that also pavement stiffness is a factor that must be considered
6. There are microslippage (stick-slip) effects in the tyre/road interaction that calls for consideration also of road surface microtexture (dry and wet friction)
7. Road surface conditions, such as rutting, wetness (water depth) and snow cover affect RR
8. For road management purposes one cannot rely on direct measurements of RR; it is better to develop a model by which RR can be predicted from collected road pavement data, the latter of which is already made to a large extent in many European countries
9. A tyre/road interaction model for RR must include a great number of road pavement, condition and geometrical parameters
10. Two main methods are used for testing RR related to road pavements: the trailer method and the coastdown method
11. MIRIAM has access to three different trailers for car tyres and one for truck tyres. All of them have unique features which are not fully compatible. It is recommended to conduct one or more round robin tests to compare these devices and methods; also including the coastdown of vehicles

Some problems to study in the further work of SP 1 of MIRIAM are:

a. The trailers measure a major part of rolling resistance, but more studies are needed to see what they might miss (if anything)

b. The trailers seem to measure the part of rolling resistance related to macrotexture with high repeatability, but it is unclear what part of megatexture and unevenness they measure

c. Especially, it must be studied how much losses there are in the suspension systems and its relation to road megatexture and unevenness, and how trailers pick-up this effect

d. The effects of road gradient and wind on trailer measurements should be studied

e. The source models that are coming out of the measurements with coastdown vehicles must be studied more, to get more accurate data and understand the mechanisms better

f. Road properties with a potential influence on rolling resistance and which must be explored more include stiffness and microtexture (friction)

g. Relations between results obtained with the various methods, and even within the trailer methods, must be studied

h. The effect of air, road and tyre temperatures on rolling resistance must be studied more, and corrections be developed
i. Calibration methods must be studied and developed more, to make sure that absolute levels of rolling resistance can be measured with sufficiently high repeatability and reproducibility

j. The trailer and the coastdown methods, as well as simultaneous measurement of all relevant road properties, should be tested in parallel in order to learn better what part of the rolling resistance and maybe suspension losses that are really measured by the trailers

k. There is a lack of reference surfaces for RR measurements of tyres and reference tyres for RR measurements of road surfaces. It is recommended to work out specifications for such in MIRIAM. One may then start by considering the use of the same reference tyres and reference surface as used for noise as one possible option.
19 LITERATURE

This chapter provides recommendations for reading about rolling resistance of tyres and the tyre/road interaction. The literature listed here is considered as extra useful.

Especially, the editor recommends the book published by Michelin. The only thing which is a problem in this book is that the many details given there generally lack references, which means that it is impossible for the reader to check-up the information against the source. Nevertheless, it is a very comprehensive reference book which contains a wealth of both qualitative and quantitative information which nobody working in this area should miss. The book is very richly illustrated by high-quality figures and diagrams in colour.


Michelin (2003): "The tyre - Rolling resistance and fuel savings". Book published by Société de Technologie Michelin, 23 rue Breschet, FR-63000 Clermont-Ferrand, France (this is also available on CD).


20 REFERENCES


Arnberg, Peter; Ohlsson, Evert; Råhs, Knut; Urberg, Mats; Åström, Gert; Östergren, Roland (1980): "Cykeldäcks slitstyrka, friktion och rullmotstånd". VTI Rapport No 201, Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.

Bachmann, Christian (2011): Personal communication with Dipl.-Ing. Christian Bachmann, Institut für Kraftfahrzeuge - RWTH Aachen University, Group Leader Tyre Technology, Chassis Department, University of Aachen, Germany.


Bergiers, Anneleen (2011): Measurement results provided by Dr Anneleen Bergiers, BRRC, to the MIRIAM SP 1 group.


Boujard, Olivier (2009): "Influence of road characteristics on rolling resistance – Literature survey" (translation of corresponding title in French). CETE de l'Ouest, Laboratoire Régional d'Angers, Unité Matériaux et Chaussées, France.


Haider, Manfred; Conter, Marco; Glaeser, Klaus-Peter (2011): "Discussion paper – 'What is rolling resistance and other influencing parameters on energy consumption in road transport'? MIRIAM Deliverable D 5.2.1, under production, will be downloadable from http://www.miriam-co2.net/index.htm


Hammarström, Ulf; et al. (2009): "Road surface effects on rolling resistance – coastdown measurements with uncertainty analysis in focus". ECRPD Deliverable D5(a), 2009-04-16.


Liukkula, Mikko (2010): Personal communication with Mr Mikko Liukkula at Nokian Tyres in Finland.


Sandberg, Ulf (2009): "MIRIAM - Models for rolling resistance In Road Infrastructure Asset Management system". Presentation at the Meeting of AFD90 in Washington, DC, USA, 13 January 2010. Can be downloaded from: http://docs.google.com/viewer?a=v&pid=sites&srcid=ZGVmYXVsdGRvbWFpbnx0cmJjb21taXR0ZWWvZmQ5MHxneDozOGJjN2RjZTRmMmY0


Siltanen, Teppo (2010): Personal communication with Mr Teppo Siltanen, Nokian Tyres, Finland (2010-05-25).


