2020

WEBINAR SERIES

RPUG
Road Profile Users' Group

RPUG Road Profile Users' Group
The 101 Sessions

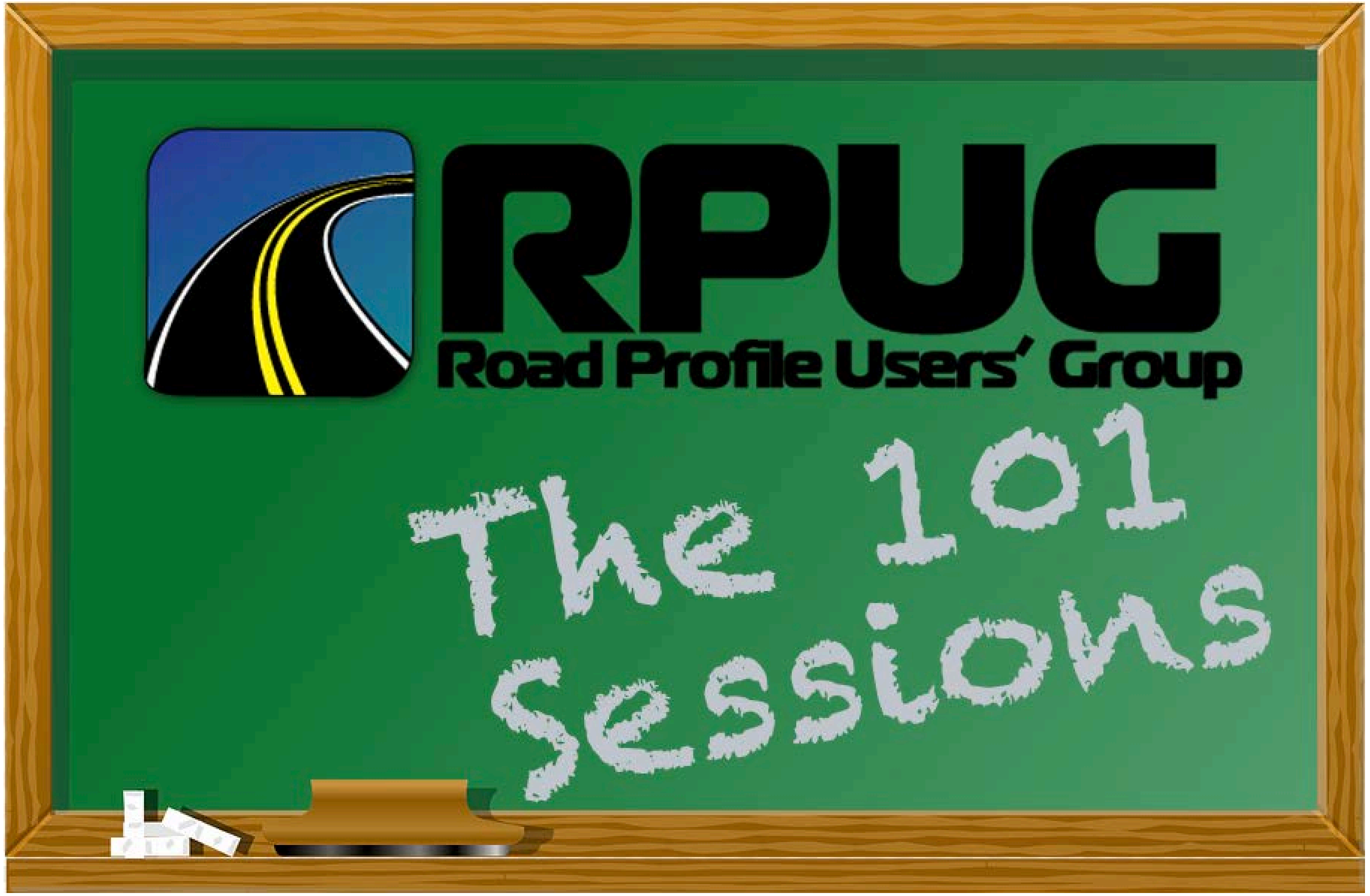
Rolling resistance 101

Richard Wix, Australian Road Research Board, 16 September 2020

A **brief** introduction to rolling resistance

The TDF edition

- Who cares about rolling resistance?
- What is it?
- How is it measured?
- How can we reduce rolling resistance?



Roll on down the highway

Theme song

We rented a truck and a semi to go,

Travel down the long and the winding road…..

Let it roll down the highway

Let it roll down the highway

Let it roll

Let it roll

Let it roll

Let it roll

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Who cares about rolling resistance?

Cyclists

09/09/2020 - Tour de France 2020 - Etape 11 - Châtelaillon-Plage / Poitiers (167,5 km) - Caleb EWAN (LOTTO SOUDAL) - Vainqueur de l'étape © A.S.O./Alex Broadway

Who cares about rolling resistance?

Hotwheels

Who cares about rolling resistance?

Roller skaters

https://www.lifehacker.com.au/2020/05/how-to-start-roller-skating-without-breaking-anything/

Who cares about rolling resistance?

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Trains

Who cares about rolling resistance?

The environment

Who cares about rolling resistance?

Electric vehicles

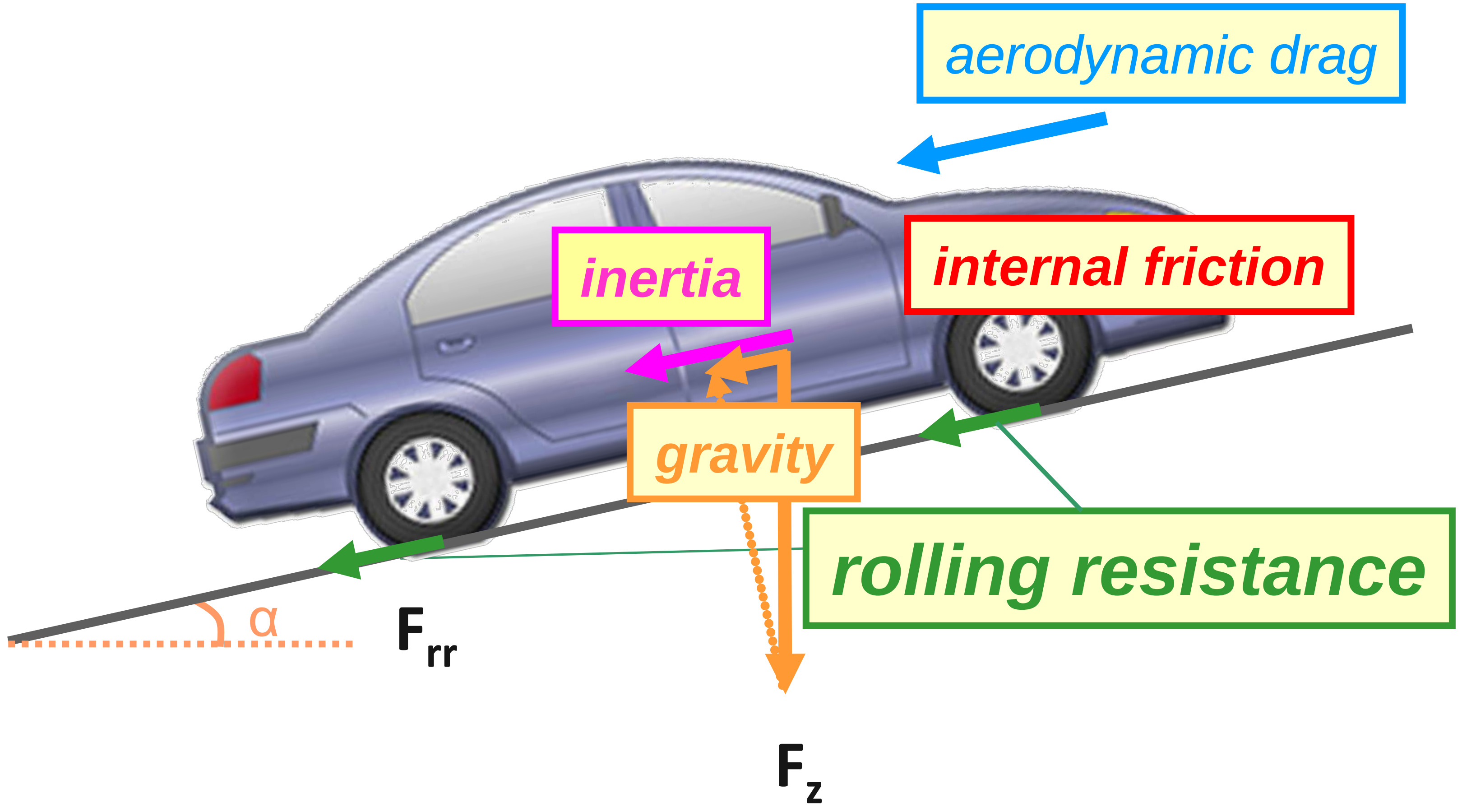
Question time - number 1

What are 5 things that stop us from rolling down the highway?

1. Inertia
2. Gravity
3. Aerodynamic drag
4. Internal friction
5. Rolling resistance

Driving resistance

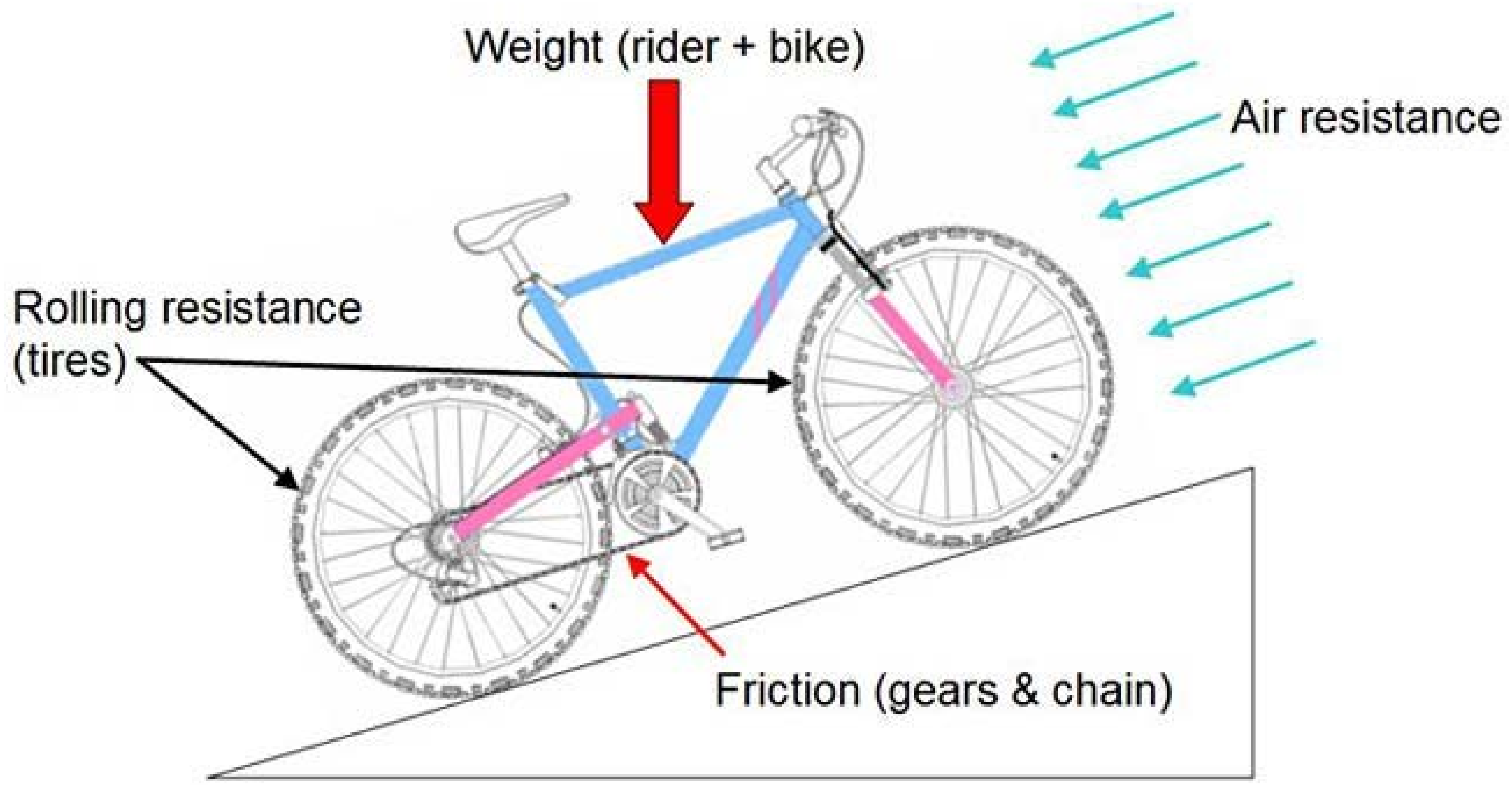
Forces



S. Köppen, ISO 28580 Working Paper No. STD-01-05, 1st STD meeting, 23 July 2009, agenda item 4

Riding resistance

Bike



(mountain bike image credit: Wikimedia Commons, user Ralf Roletschek)

Pavement Life Cycle Assessment

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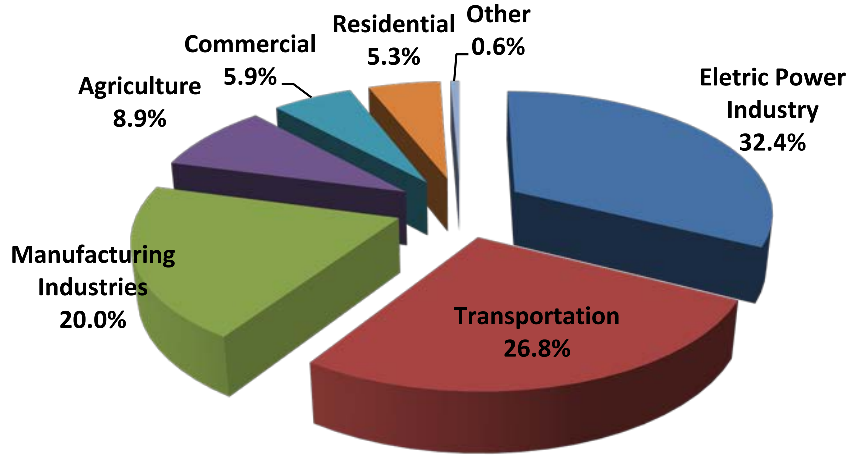
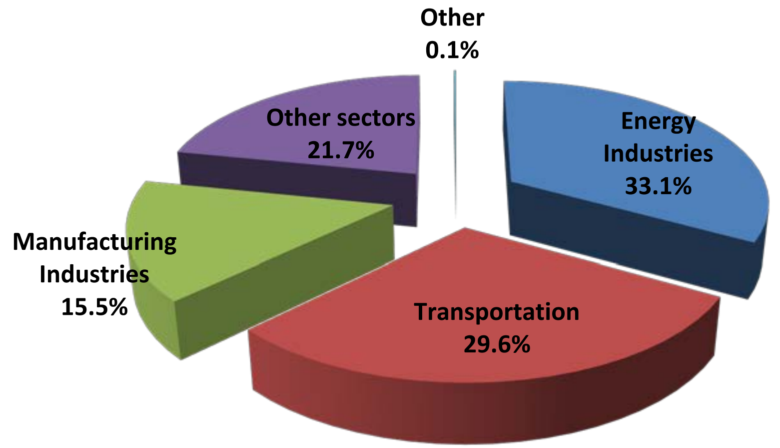
U.S. CO_2-eq emission by sector (2011) [1]



Italy CO_2-eq emission by sector (2011) [2]



[1] U.S. EPA. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013. Technical report, U.S Environmental Protection Agency, 2015.

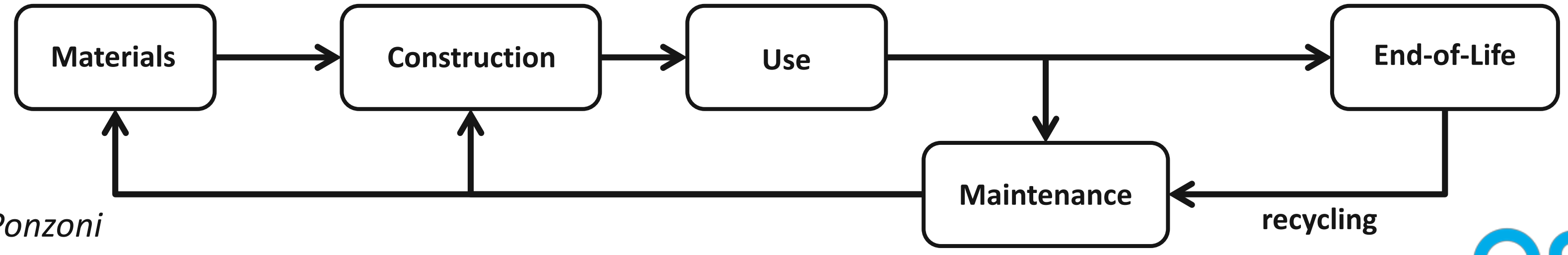
[2] ISPRA. Italian Greenhouse Gas Inventory 1990-2012 National Inventory. Technical report, Istituto Superiore per la Protezione e la Ricerca Ambientale, 2014.

- Extraction and Production
- Transportation

- Onsite equipment
- Traffic delay

- Embodied emissions
- Extraction and Production
- Carbonation
- Albedo
- Lighting
- Rolling Resistance

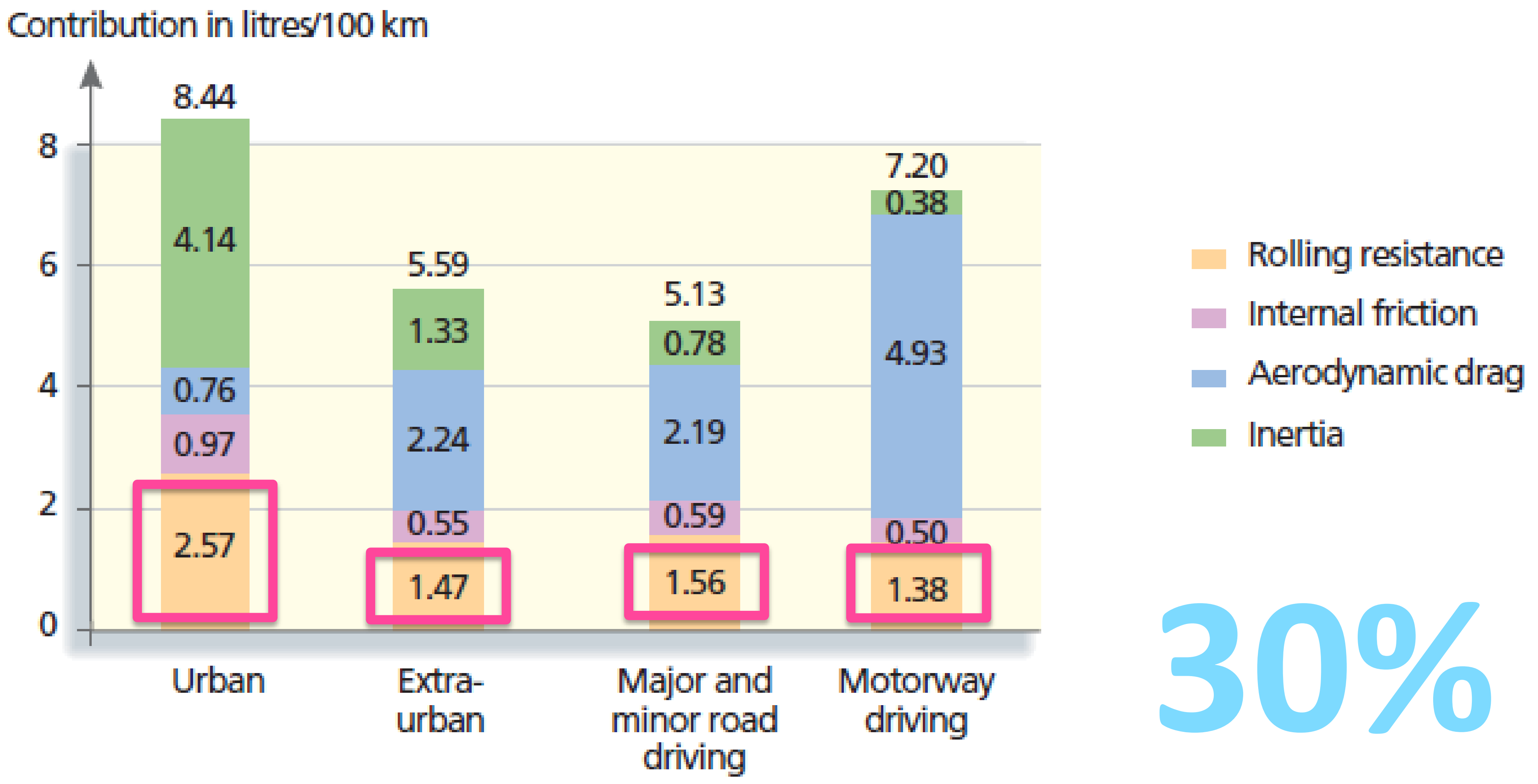
- Landfilling
- Transportation



Slide courtesy of Federico Ponzoni

Fuel consumption

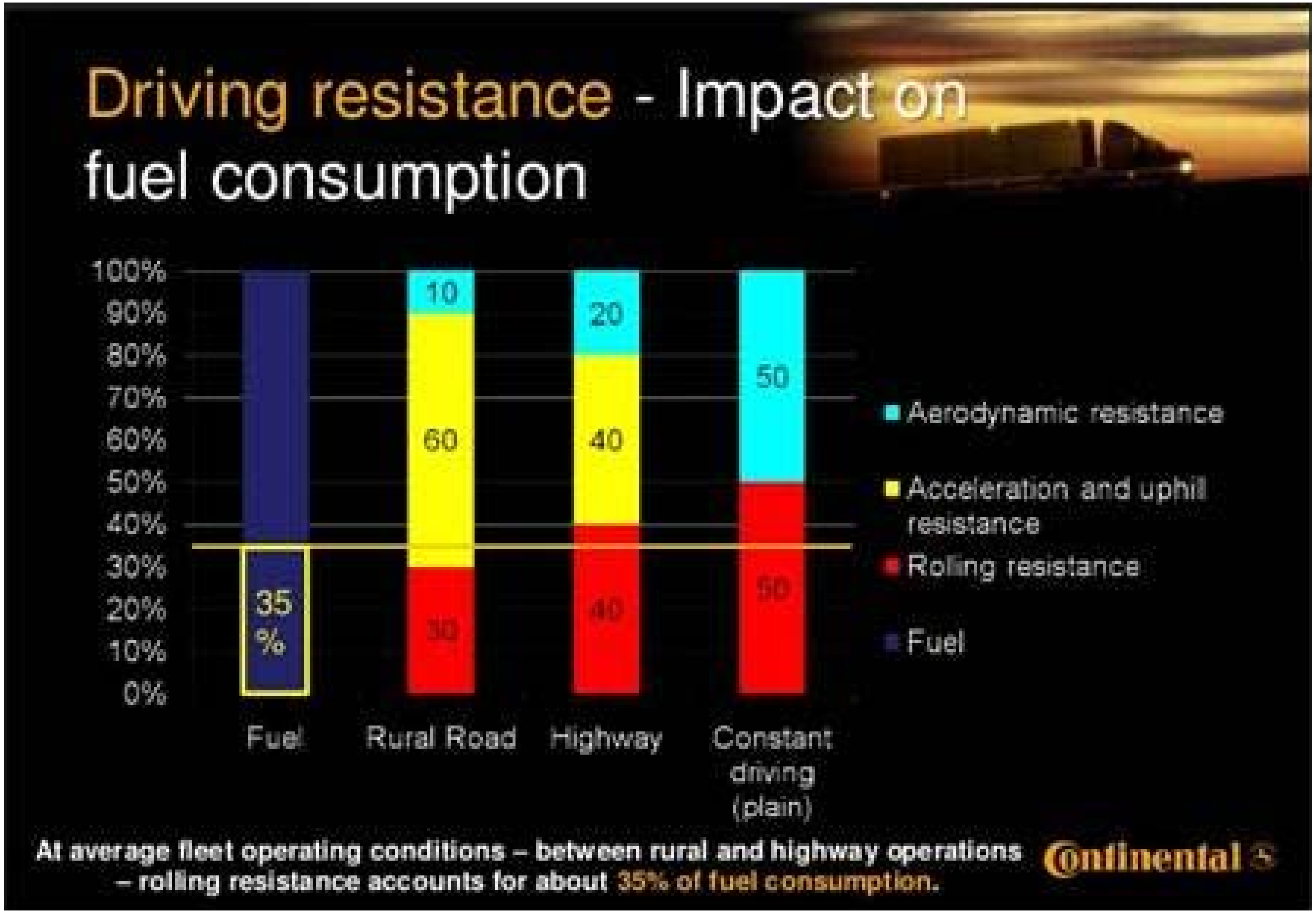
Contributors to fuel consumption expressed in l/100 km (Michelin, 2003)



30%

Driving resistance

Impact on fuel consumption

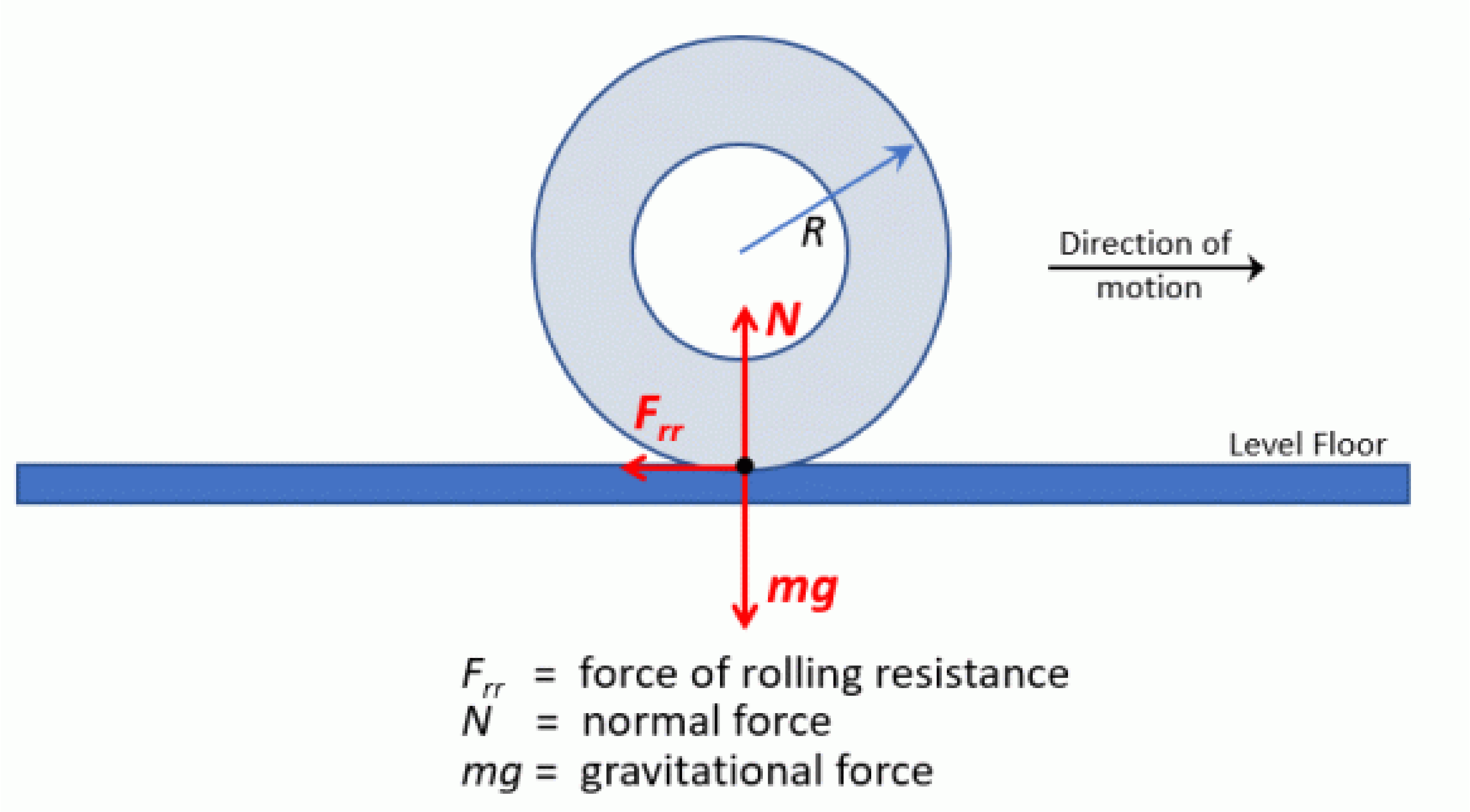


Vehicle wheels

Progression through the ages

Rolling resistance

Coefficient of rolling resistance coefficient (C_r)



$$F_{rr} = C_r \; x \; N$$

$$C_r = Fr_r / N$$

Coefficient of rolling resistance

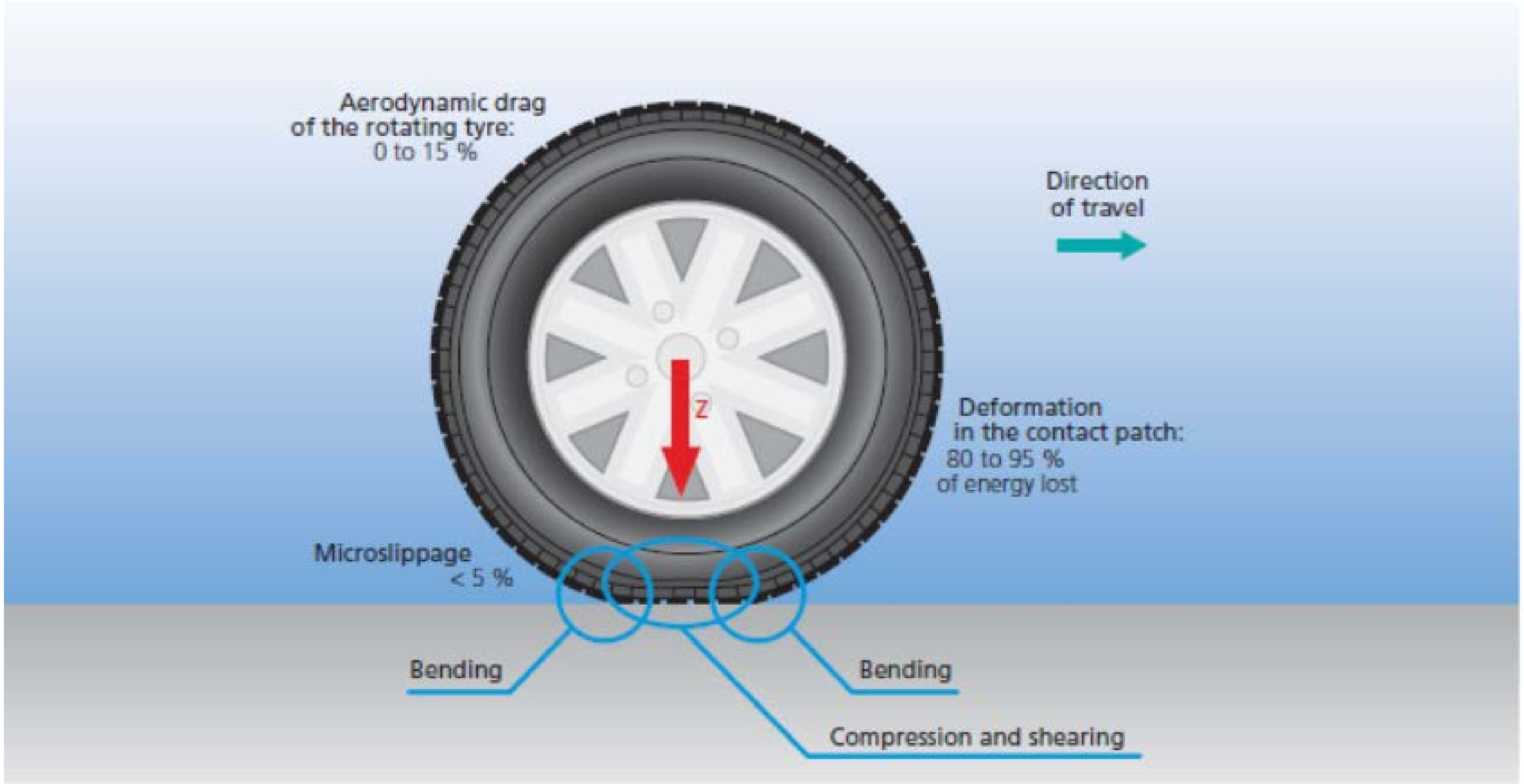
Variations

Value (C_r)	Description
0.001 - 0.002	railroad steel wheels on steel rails
0.001	bicycle tire on wooden track
0.002 - 0.005	low resistance tubeless tires
0.002	bicycle tire on concrete
0.004	bicycle tire on asphalt road
0.005	dirty tram rails
0.006 - 0.01	truck tire on asphalt
0.008	bicycle tire on rough paved road
0.01 - 0.015	ordinary car tires on concrete, new asphalt, cobbles small new
0.02	car tires on tar or asphalt
0.02	car tires on gravel - rolled new
0.03	car tires on cobbles - large worn
0.04 - 0.08	car tire on solid sand, gravel loose worn, soil medium hard
0.2 - 0.4	car tire on loose sand

engineeringtoolbox.com

What causes of rolling resistance?

Pneumatic tires



What causes of rolling resistance?

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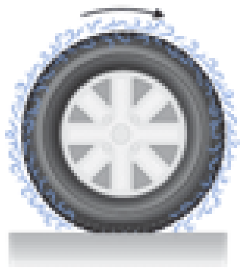
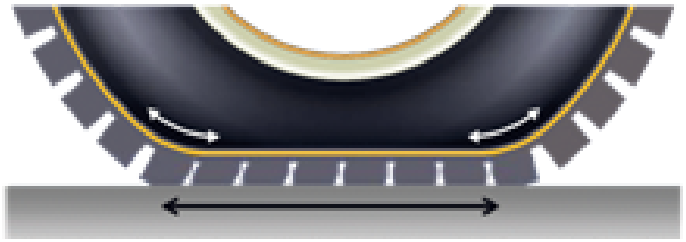
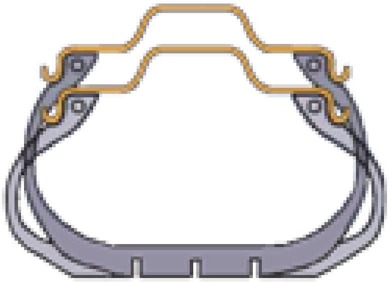
Breakdown of tire properties contributing to rolling resistance

What	Surface of tire and air	Tire tread				Sidewall and bottom part	
How	Air circulation	Slippage on ground	Deformation hence dissipation of energy				
			bending	compression	shearing	bending	shearing
							
Contri-bution	< 15%		60 to 70%			20 to 30 %	

https://thetiredigest.michelin.com/michelin-ultimate-energy-tire

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Question time - number 2

What properties of a tire affect rolling resistance?

1. Tread
2. Compound (stiffness)
3. Pressure/contact area
4. Load
5. Speed
6. Temperature

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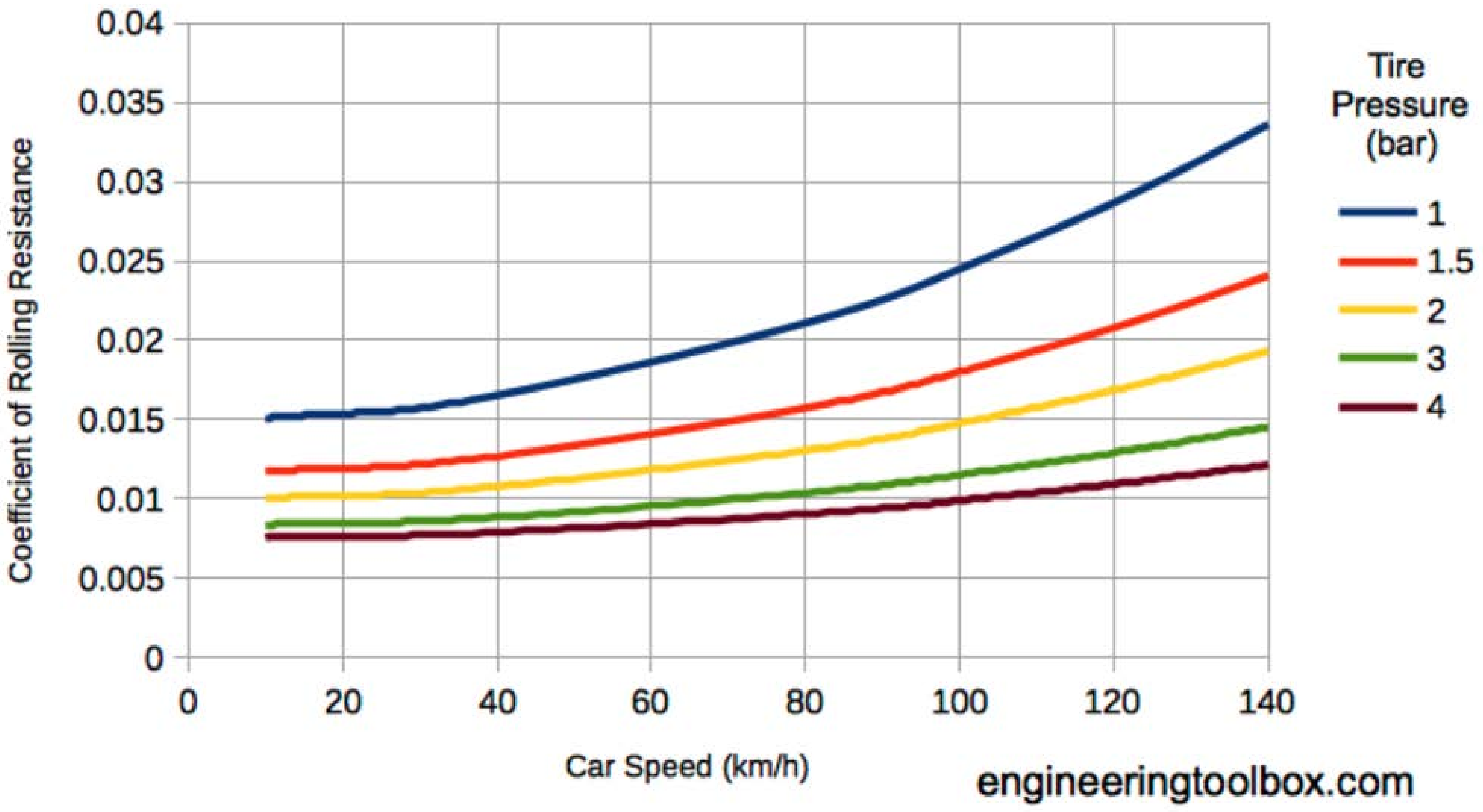
Vehicle speed & pressure

Passenger vehicles



Vehicle speed & pressure

Bikes

Rolling Resistance Test Results

Rolling Resistance Test Results	
Inner Tube	Conti Race28 (100gr butyl)
Rolling Resistance 140 PSI / 9.7 Bar	**Not Tested** CRR: Not Tested
Rolling Resistance 120 PSI / 8.3 Bar	**18.0 Watts** CRR: 0.00540
Rolling Resistance 100 PSI / 6.9 Bar	**18.8 Watts** CRR: 0.00564
Rolling Resistance 80 PSI / 5.5 Bar	**21.0 Watts** CRR:0.00629
Rolling Resistance 60 PSI / 4.1 Bar	**24.7 Watts** CRR: 0.00740

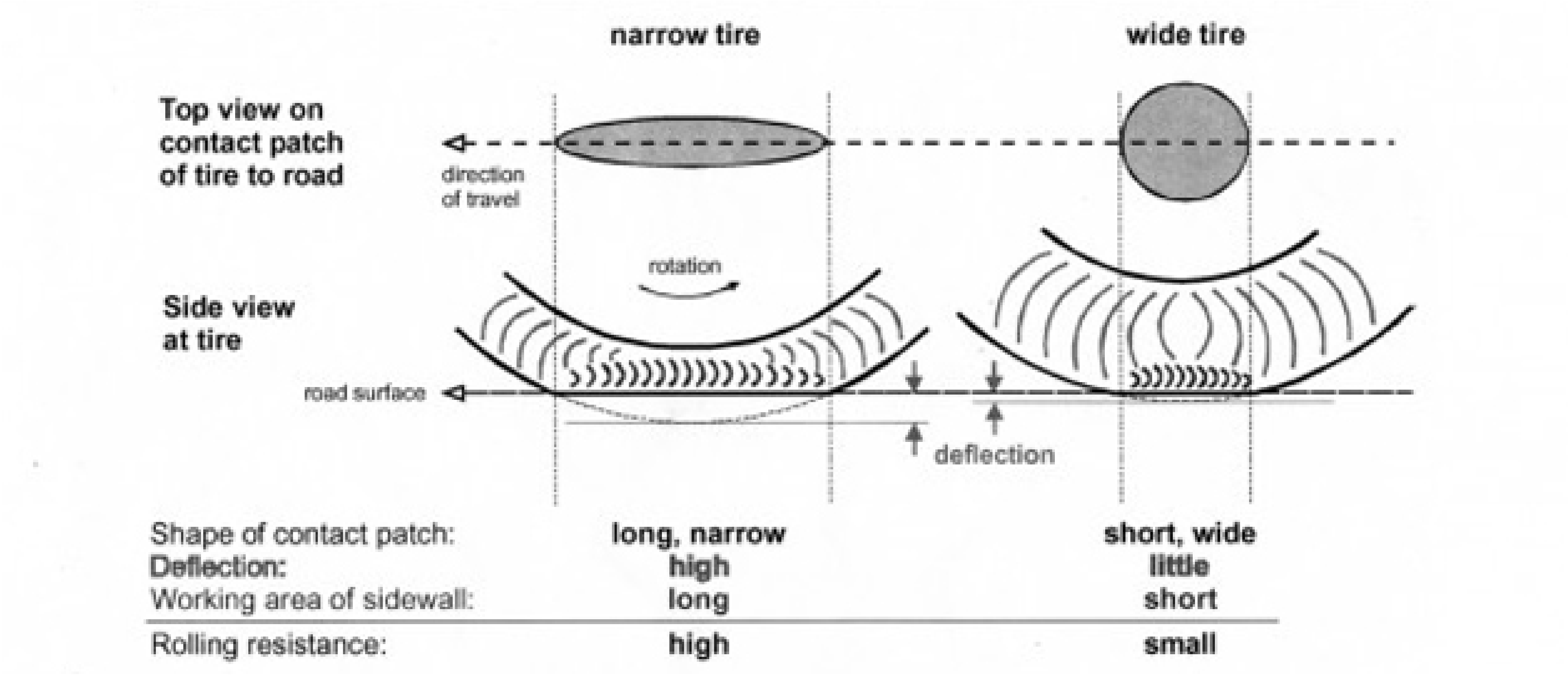
All numbers are for a **single tire** at a speed of 29 km/h / 18 mph and a load of 42.5 kg / 94 lbs.

Use the formula: **RR (Watts) = CRR * speed (m/s) * load (N)** to calculate rolling resistance at a given speed and load.

https://www.bicyclerollingresistance.com/road-bike-reviews/schwalbe-durano-2015

Question time – number 4

How does bicycle tire width relate to rolling resistance?



Question time – number 5

Rolling resistance predominantly generates:

- Heat

Time for some maths

Just how much difference does a lower coefficient of rolling resistance make?

$C_r = 0.02$	Car tires on tar or asphalt
$C_r = 0.001 - 0.002$	Railroad steel wheels on steel rails

Force required to keep a 2 tonne passenger vehicle rolling:

$F_{rr} = 0.02 \text{ x } (2000 \text{ kg}) \text{ x } 9.81 \text{ m/s}^2$

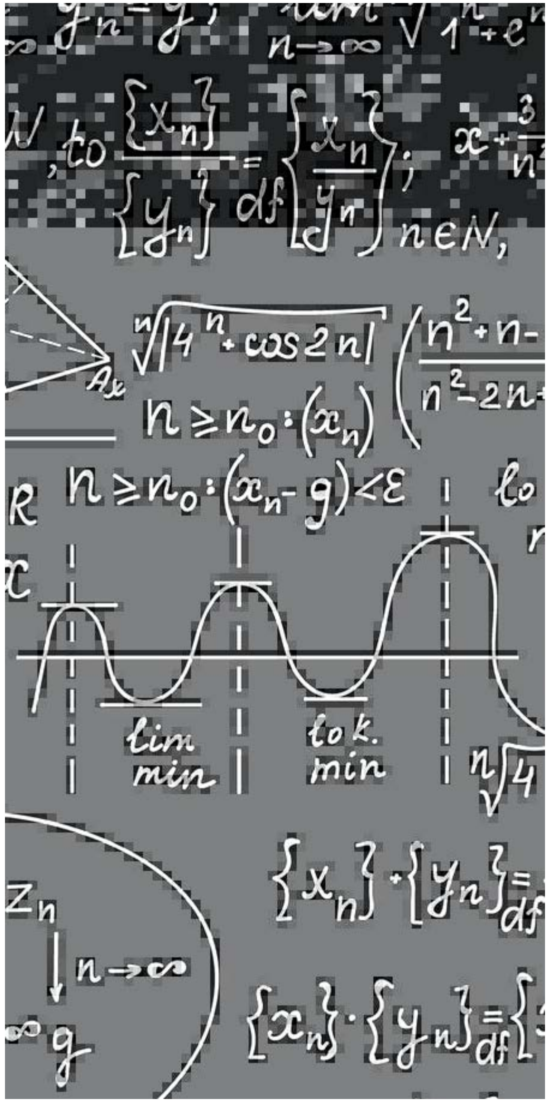
$= 392 \text{ N}$

Force required to keep a 100 tonne railroad car rolling:

$F_{rr} = 0.001 \text{ x } (100{,}000 \text{ kg}) \text{ x } 9.81 \text{ m/s}^2$

$= 981 \text{ N}$

$$F_{rr} = C_r \, x \, mg$$



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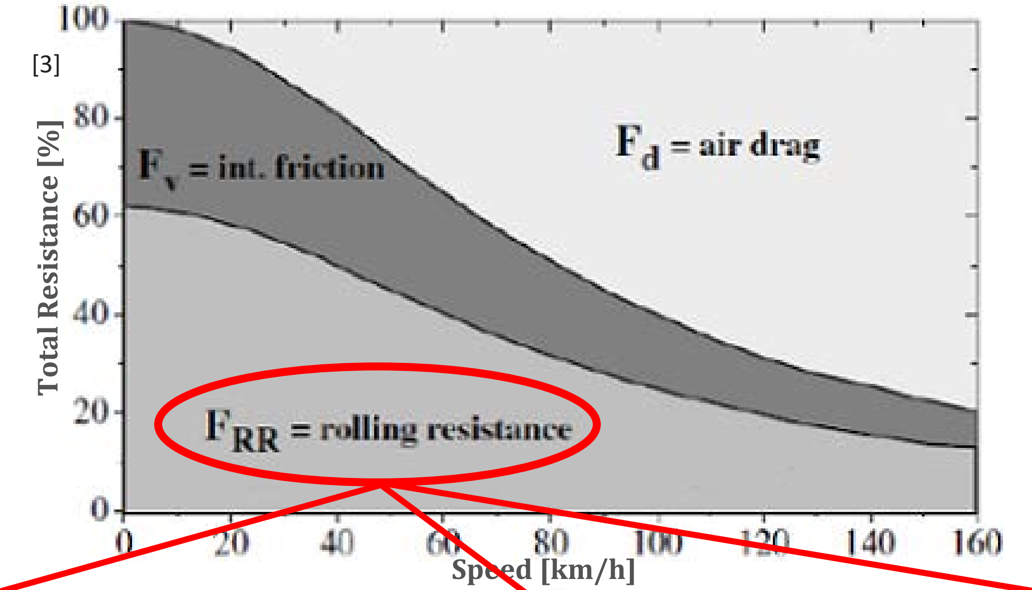
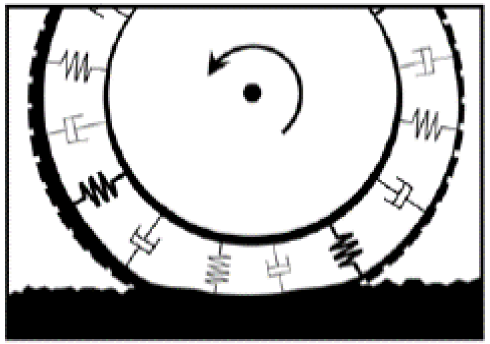
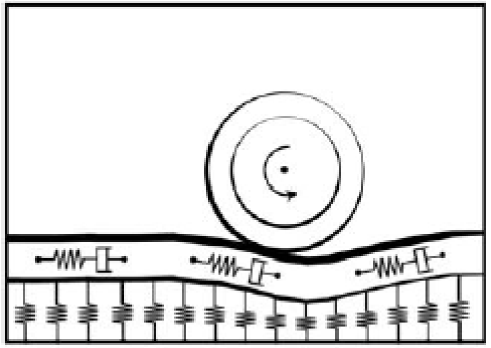
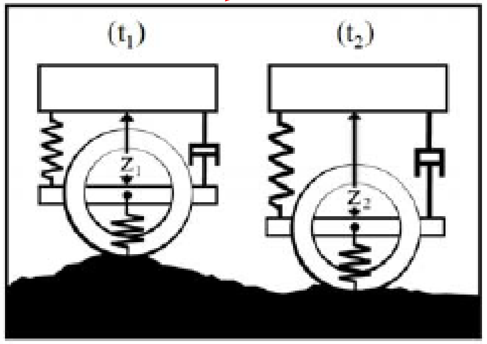
Pavement vehicle interaction



[3] E. Beuving, T. De Jonghe, D. Goos, T. Lindahl, and A. Stawiarski. Fuel efficiency of road pavements. Technical report, Eurasphalt and Eurobitume Congress, 2004.







Pavement Texture
Tire-pavement contact area.
Critical for safety.

Pavement Deflection
Speed, temperature and traffic dependent. Of critical importance for pavement design (stiffness and thickness).

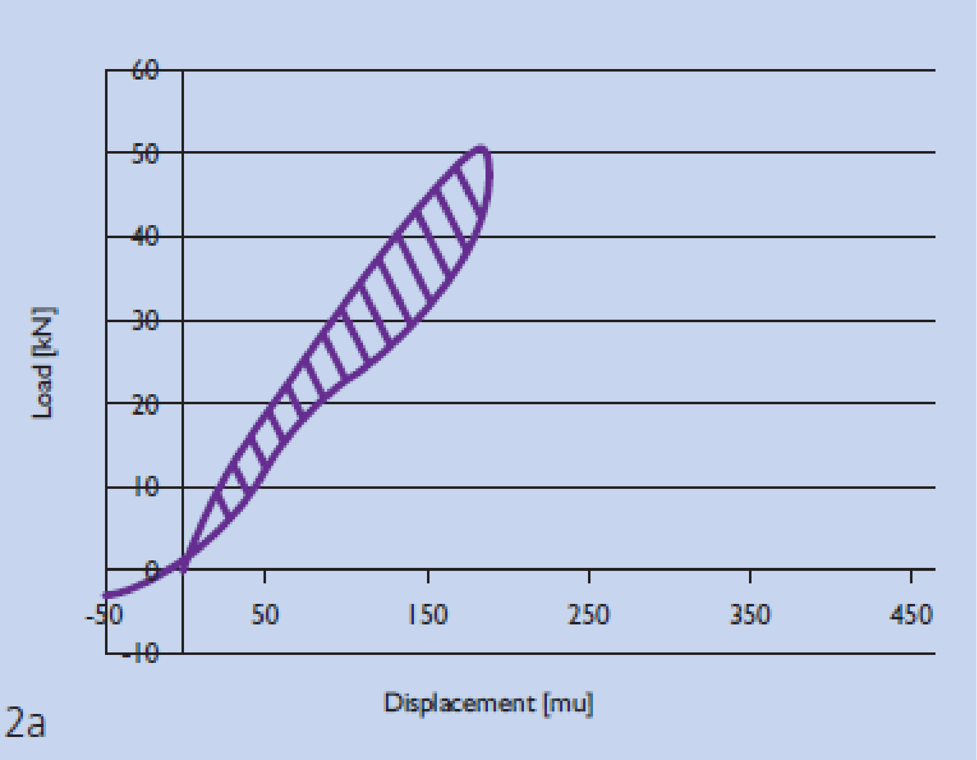
Pavement Roughness
The absolute value is vehicle dependent. Evolution over time is material specific.

Slide courtesy of Federico Ponzoni

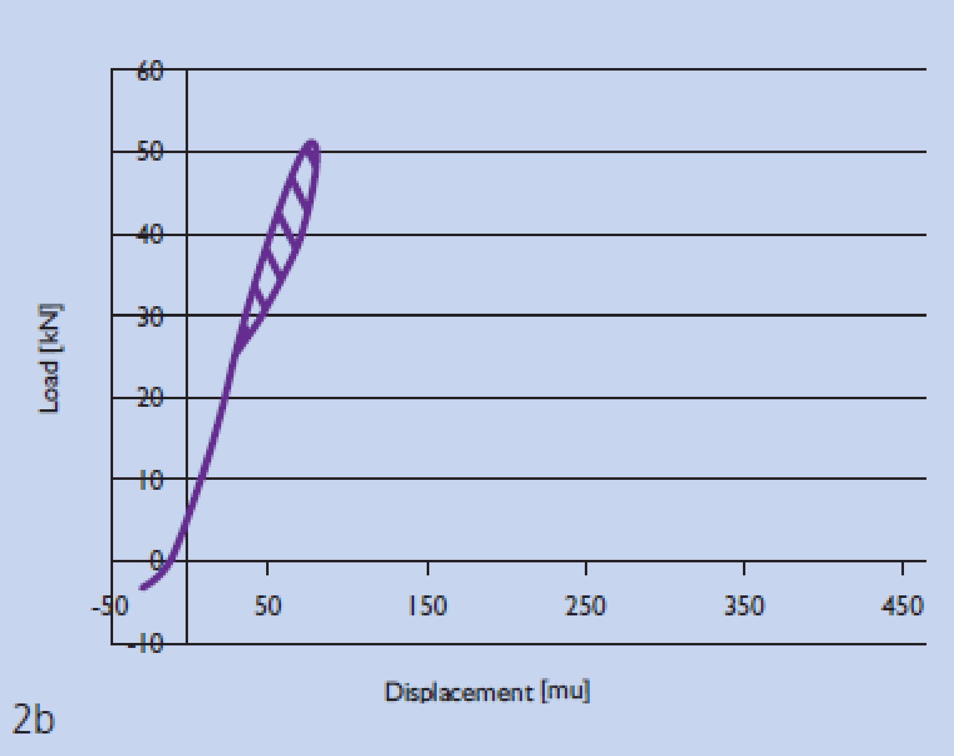
Pavement stiffness/deflection

Load deflection graphs

FWD load-deflection on a typical asphalt motorway (Lund University)



Asphalt



Concrete

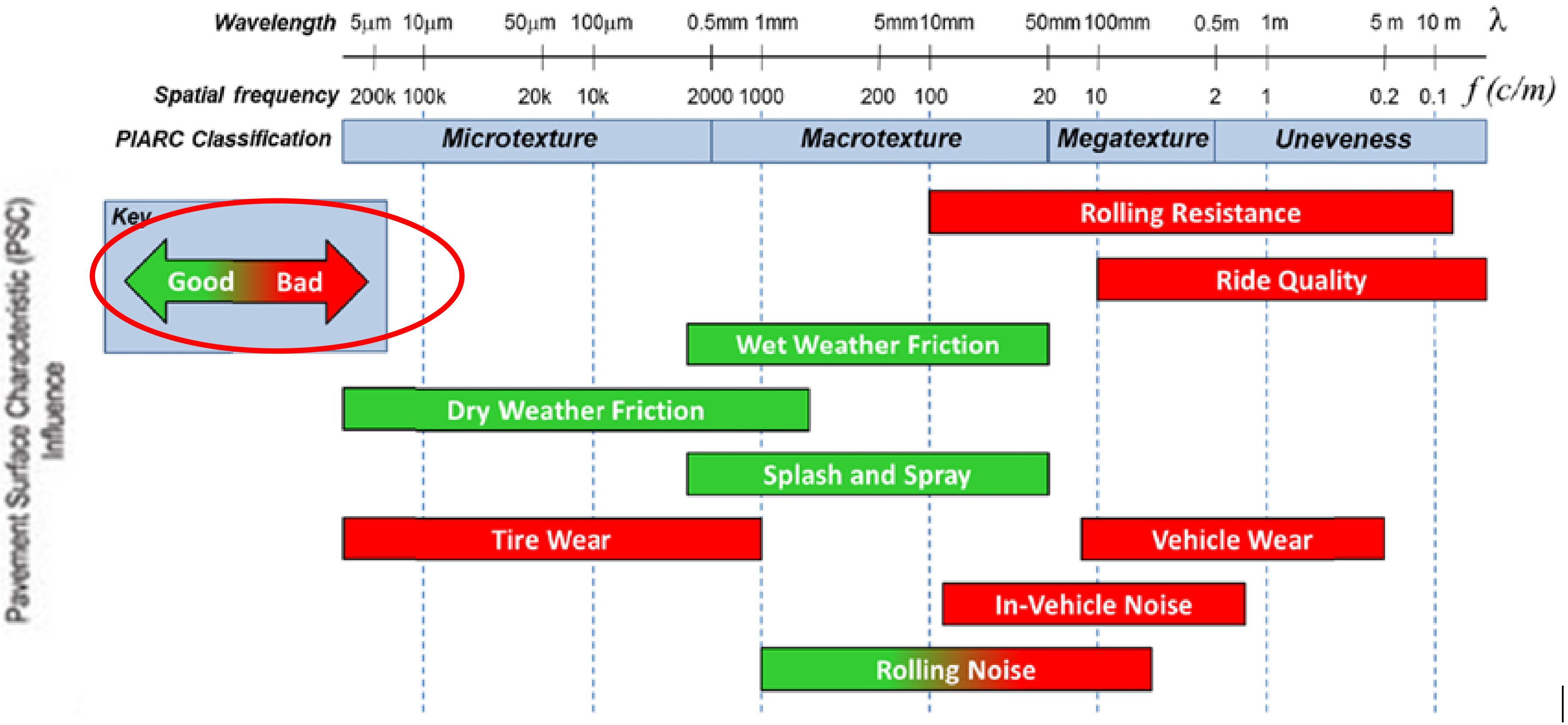
Slide courtesy of Gerardo Flintsch

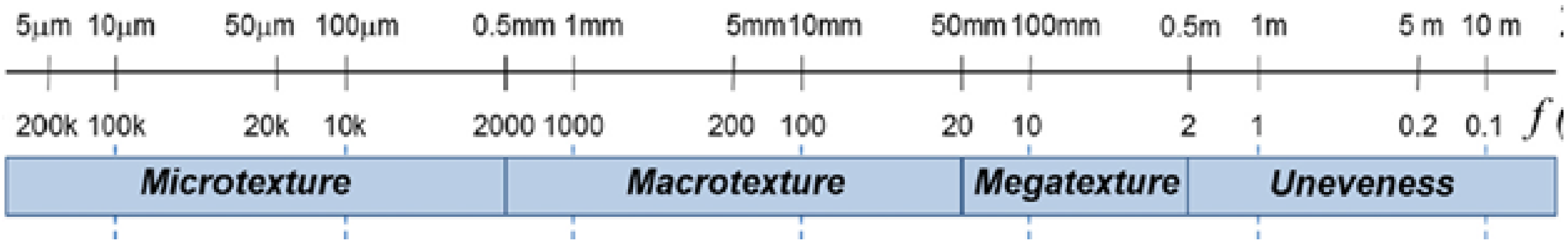
Pavement deflection

Network level assessment

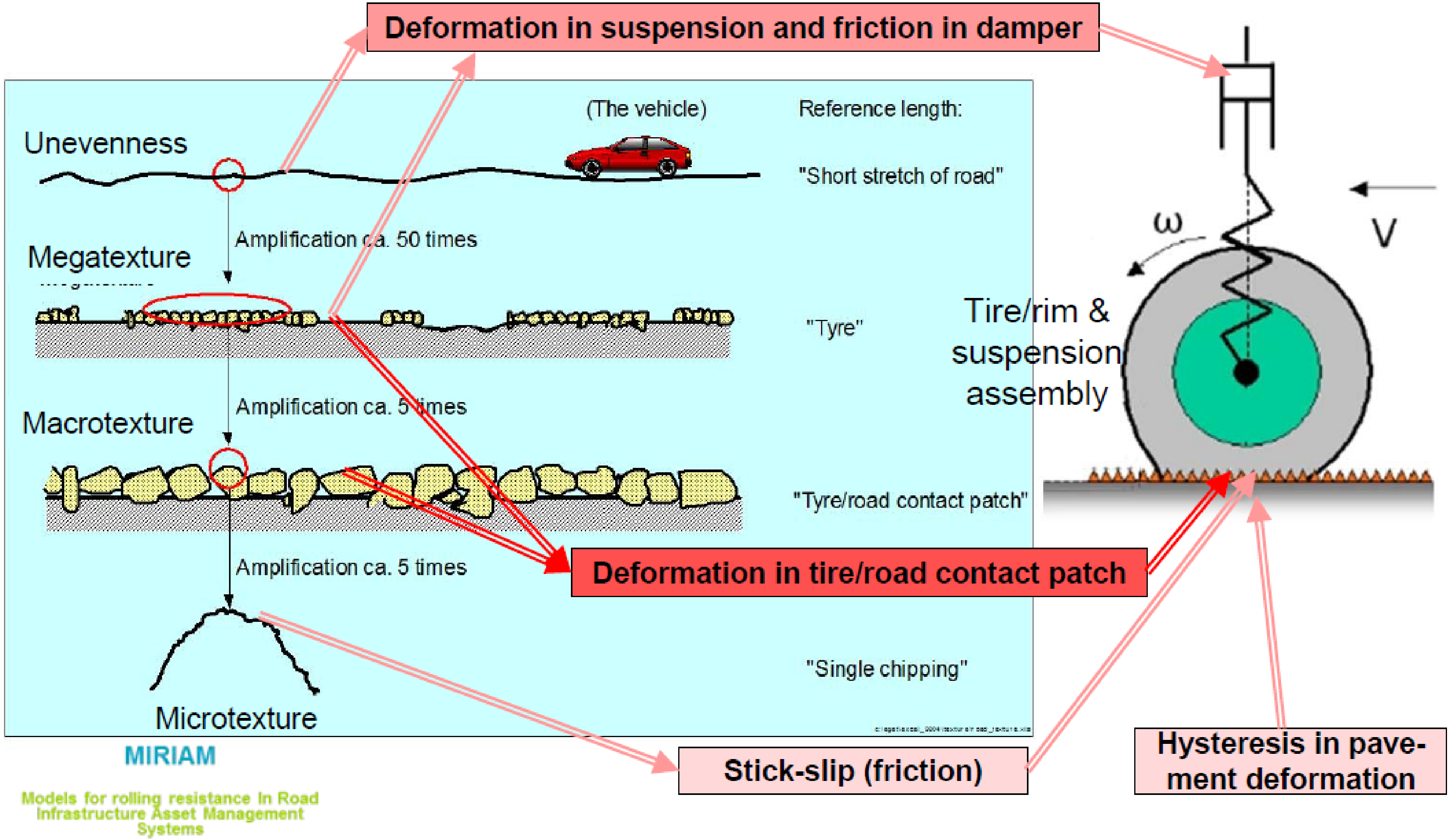
Pavement Interaction

PIARC classification and impact on pavement vehicle interaction





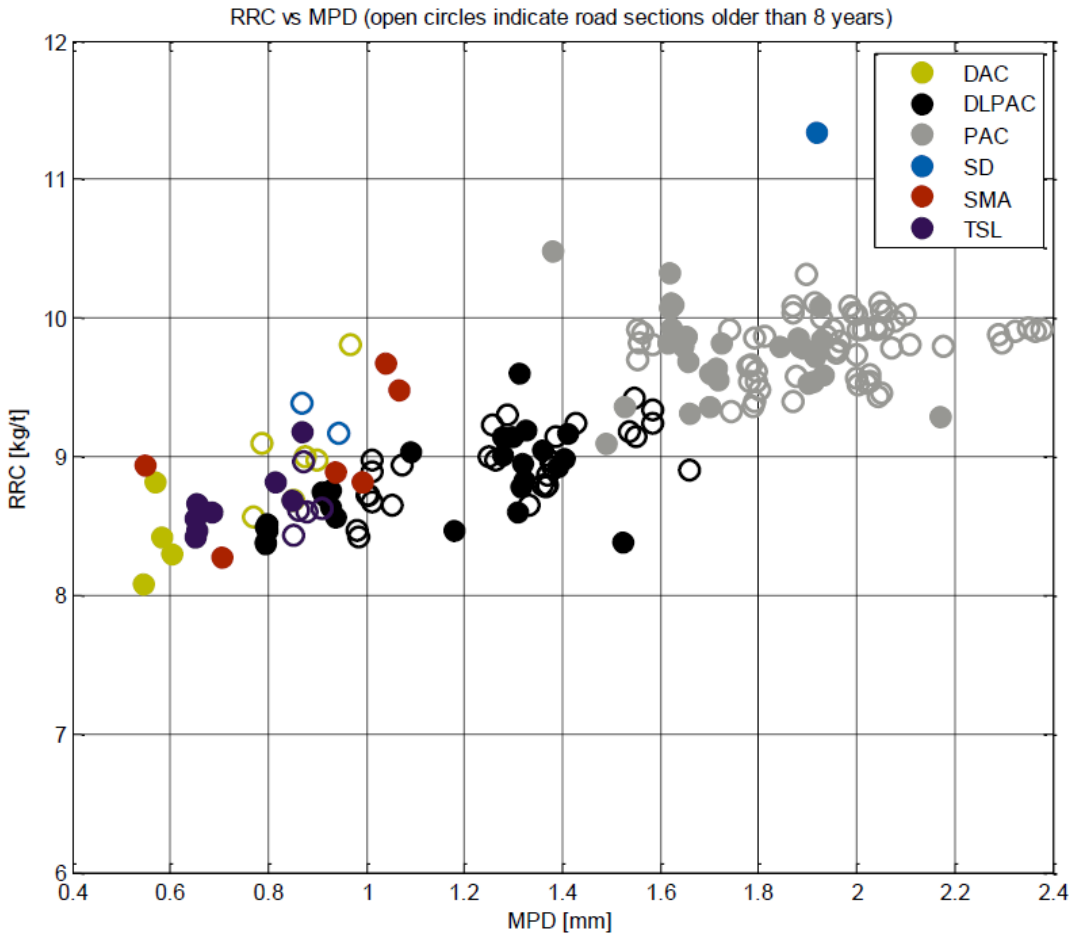
Pavement interaction

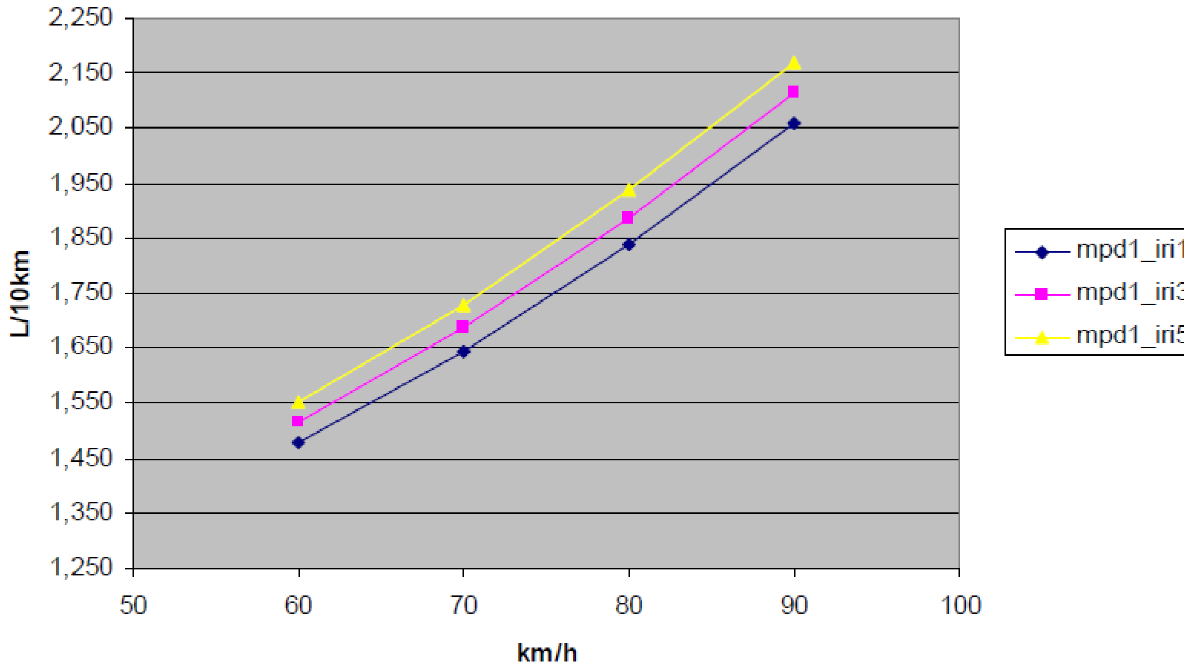


Slide taken from **'Trade-offs Between Rolling Resistance and Other Pavement Properties', Presentation by Dr Ulf Sandberg, Swedish National Road and Transport Research Institute (VTI), TRB 2012**

Effect of MPD and IRI on rolling resistance

Rolling resistance vs. macrotexture (not corrected for tire temperature) on 69 Dutch road sections. (Hooghwerff et al, 2013)



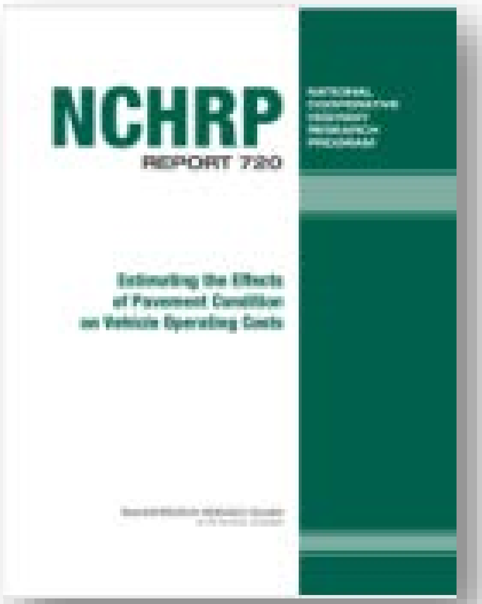


IRI influence on fuel consumption for a heavy truck at constant macrotexture (MPD) and road alignment. (Hammarström, et al., 2012)

Slide courtesy of Gerardo Flintsch

Estimating the Effects of Pavement Condition on VOC

NCHRP 720



- VOCs increase with pavement roughness for all types of vehicles and road pavement types investigated.
- IRI increase of 1 m/km →
  - Cars: 2% increase in fuel consumption of passenger cars regardless of their speed
  - Heavy trucks: 1% at highway speeds (96 km/h) and 2% at low speeds (56 km/h)
- Macrotexture only affect trucks
- MPD 1 mm increase →
  - at 88 km/h increases fuel consumption by about 1.5% and about 2% at 56 km/h

Slide courtesy of Gerardo Flintsch

Influence on rolling resistance

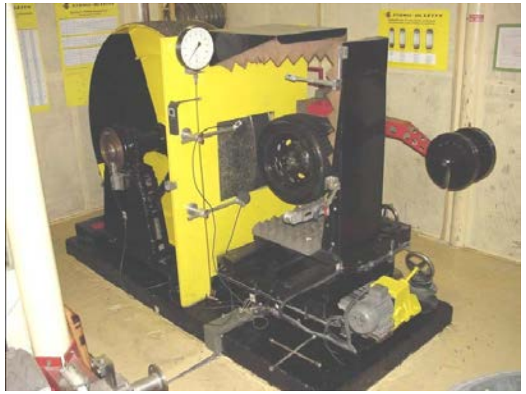
Property	Influence on rolling resistance	Trade-off
Macrotexture	Deeper macrotexture = higher rolling resistance	Worse wet skid resistance, can compromise safety
Tire pressure	Higher tire pressure = smaller contact patch = lower rolling resistance	
Smoothness	Worse smoothness = higher rolling resistance	Higher maintenance costs
Noise	Rougher macrotexture = louder pavement (except in PA courses)	
Stiffness	Higher stiffness = Less rolling resistance	Worse riding comfort

Slide courtesy of Gerardo Flintsch

How do you measure rolling resistance?

Measurement

Different methods



(Bergiers et al., 2011)

- **Laboratory drum method**
  - On the steel surface, sandpaper, replica road surfaces, etc.
- **Trailer method**
  - Special trailer equipped with a test tire
- **Coastdown**
  - Neutral and let roll until stop or until a certain speed
- **Fuel consumption**
  - influence of driving style of the driver

(Sandberg et al., 2012)

Measurement

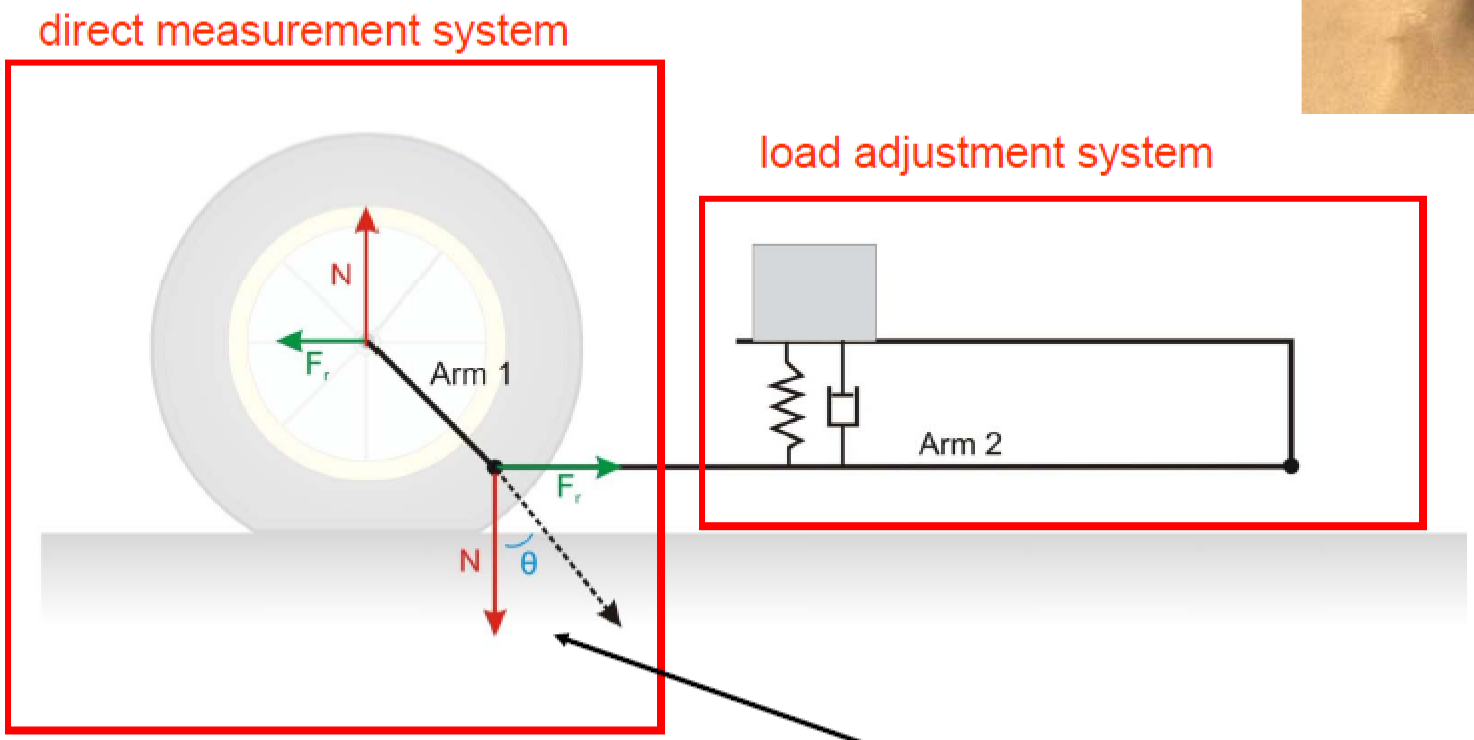
Trailer methods

Angle based (BRRC, TUG)

Force based (BASt)

Measurement

TUG angle based system



θ : orientation of Arm 1

$$RRC = \frac{F_r}{N} = \tan(\theta)$$

Comparisons

BASt versus TUG

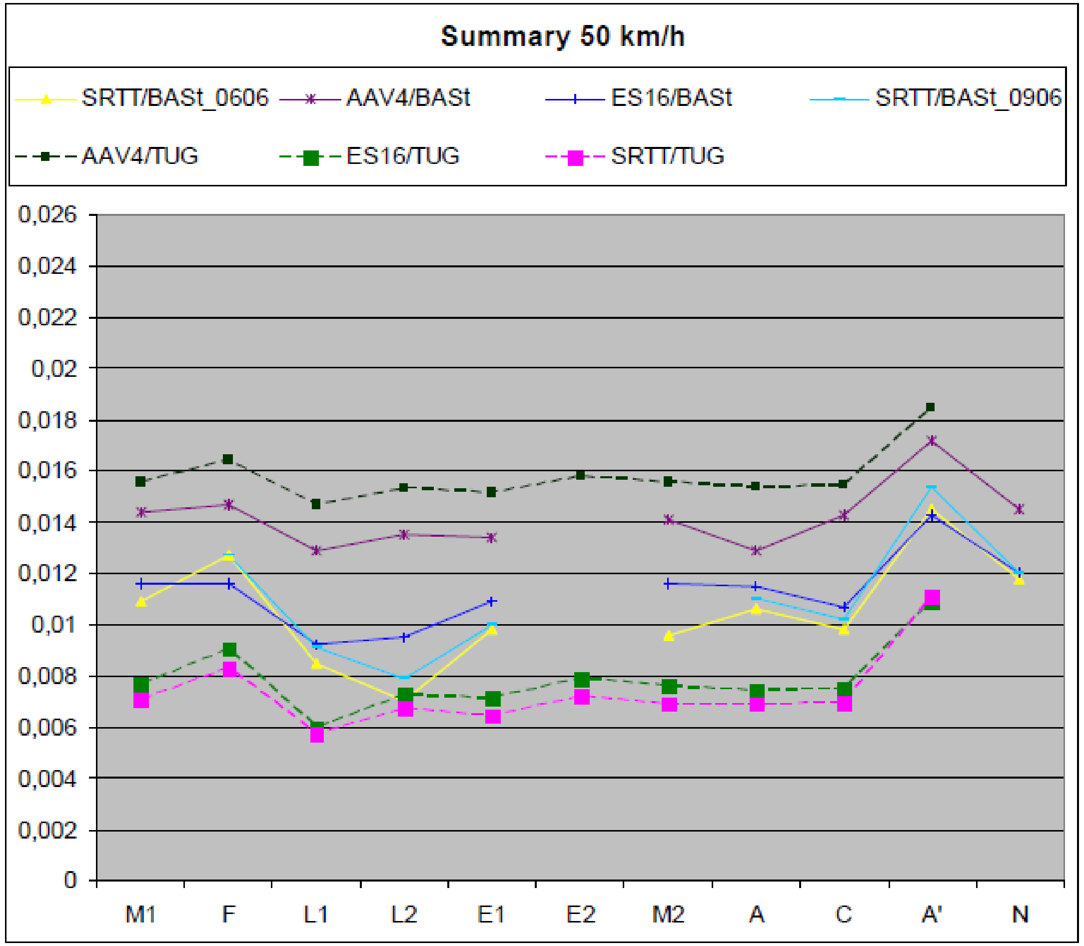


Figure 8.5: C_r for different test sections measured by BASt and TUG at 50 km/h

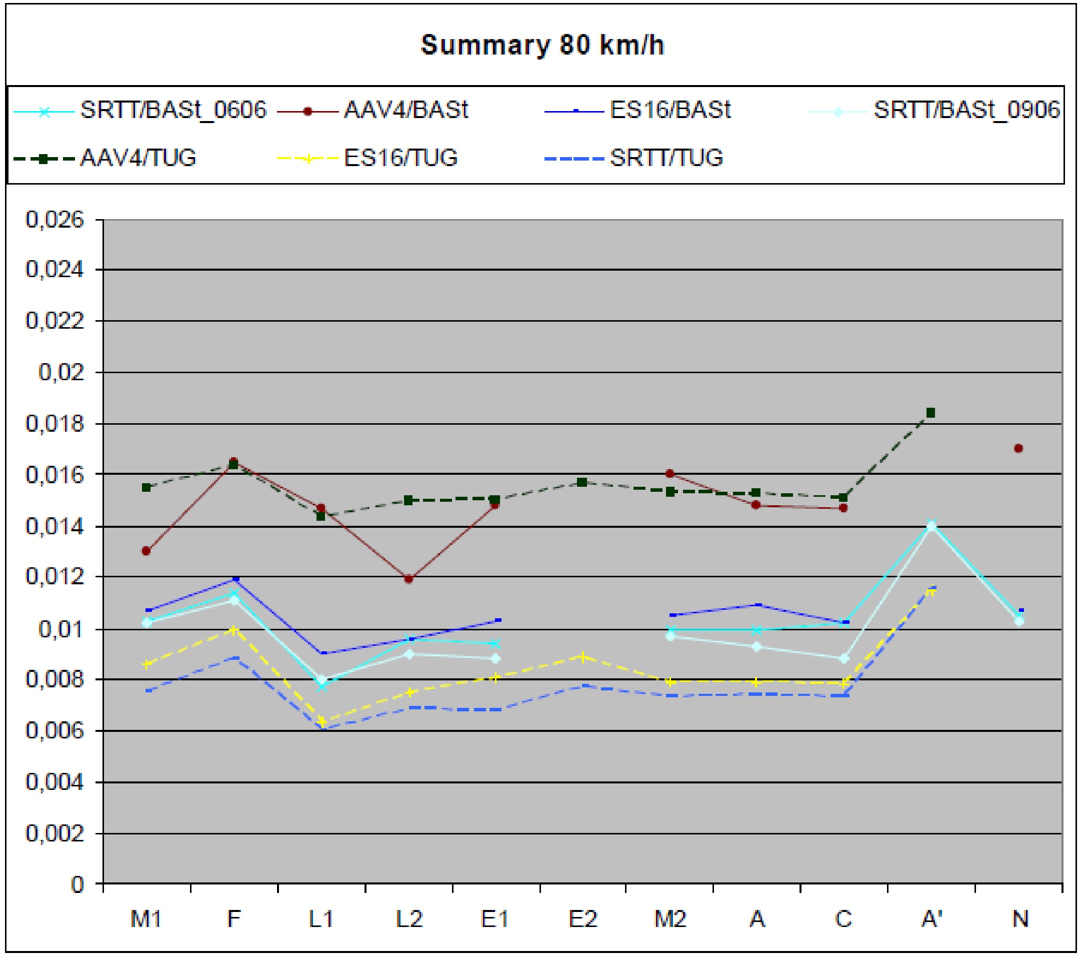


Figure 8.6: C_r for different test sections measured by BASt and TUG at 80 km/h

(Bergiers et al., 2011)

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Measurement

Coast down

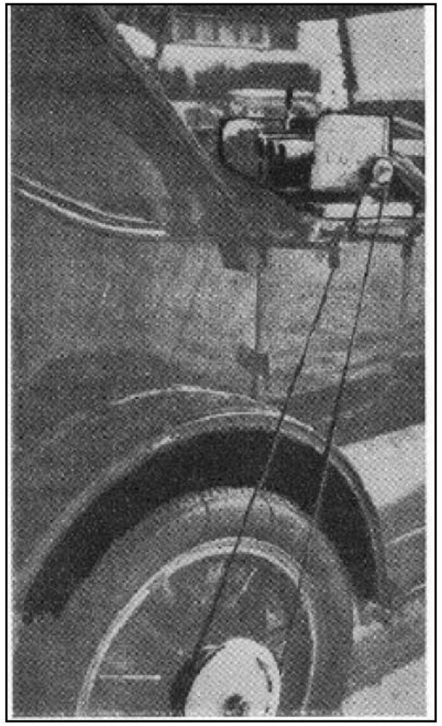
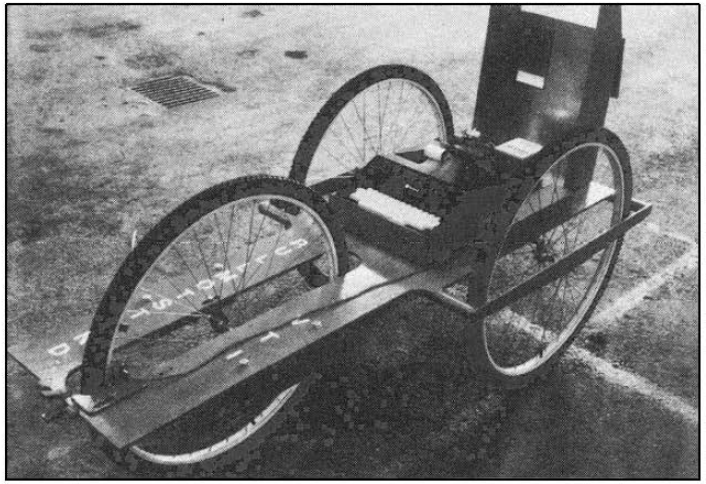


Fig. 11.1: Precision equipment "Ames Space-time Recorder" for measuring retardation (speed) during coastdown, as used by [Agg, 1928].

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.



How is rolling resistance being used in modelling?

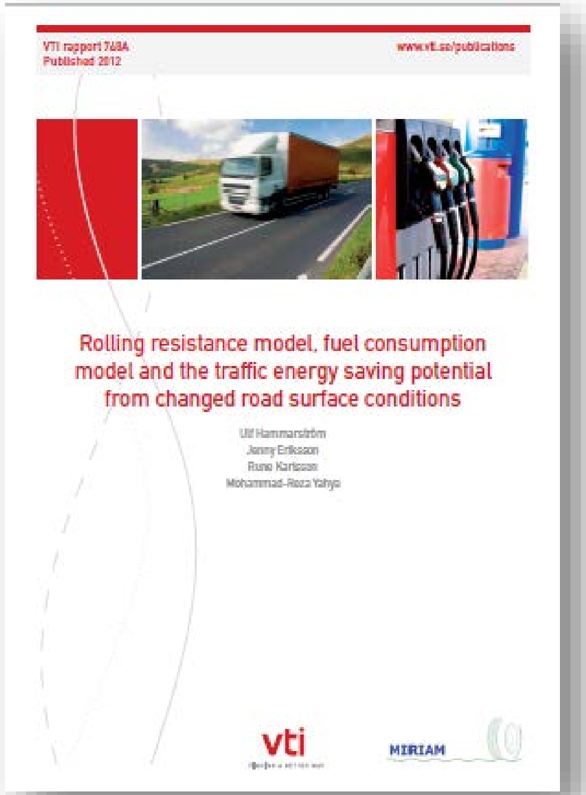
MIRIAM

Models for rolling resistance in road infrastructure asset management systems (2010 onwards)

$$F_{cs} = c1 \cdot (1 + k5 \cdot (\boldsymbol{F_r} + F_{air} + d1 \cdot ADC \cdot v^2 + d2 \cdot RF + d3 \cdot RF^2))^{e1} \cdot v^{e2-1}$$

- F_{CS}: Fuel consumption (N)
- F_{air}: Air resistance (N)
- ADC: Average degree of curvature (rad/km)
- RF: Rise and fall/gradient (m/km)
- v : Velocity (km/h)
- $\mathrm{c1, k5, d1, d2, d3, e1\ and\ e2}$: Parameters

– IRI and MPD are part of the rolling resistance function (***F$_r$***).



VTI rapport 768A
Published 2012
www.vti.se/publications

Rolling resistance model, fuel consumption model and the traffic energy saving potential from changed road surface conditions

Ulf Hammarström
Jenny Eriksson
Rune Karlsson
Mohammad-Reza Yahya

vti
MIRIAM

(Hammarström et al. 2012)

Slide courtesy of Gerardo Flintsch

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MIRIAM

Rolling resistance function (F_r)

Car:

- $F_r = m1*g*(0.00912+0.0000210*iri*v+0.00172*mpd)$

Heavy truck:

- $F_r = m1*g*(0.00414+0.0000158*iri*v+0.00102*mpd)$

Heavy truck with trailer:

- $F_r = m1*g*(0.00414+0.0000158*iri*v+0.00102*mpd)+m2*g*(0.00306+0.0000158*iri*v+0.00102*mpd)$

- Fuel consumption (90km/h) increases per increase of **MPD** unit:
  - ✓ Car: 2.8%, Heavy truck: 3.4%, Truck+trailer: 5.3%

- Fuel consumption (90km/h) increases per increase of **IRI** unit:
  - ✓ Car: 0.8%, Heavy truck: 1.3%, Truck+trailer: 1.7%

Slide courtesy of Gerardo Flintsch

ROSE - ‘Road Saving Energy’ (2016)

RPUG Road Profile Users’ Group

Creating the scientific background for a 20% reduction in rolling resistance

Motorway exiting the greater area of Copenhagen northbound towards Elsinore

- This will contribute to an additional reduction in fuel consumption
- If successful it will lead to a 1.5% reduction in energy consumption in Denmark

Slide courtesy of Bjarne Schmidt

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Some ROSE results

The value of a well maintained network

- Average state road condition in 2012:
  - Mean value of MPD: 1.08
  - Mean value of IRI: 1.27
- Average state road condition in 2015:
  - Mean value of MPD: 0.88
  - Mean value of IRI: 1.1
- Percentage reduction in fuel consumption:
  - Car: 0.65%
  - Truck: 1.02%

Increased investment by a factor 3 to 4 over a 3-year period maintaining 1/4 of the state roads to clear backlog

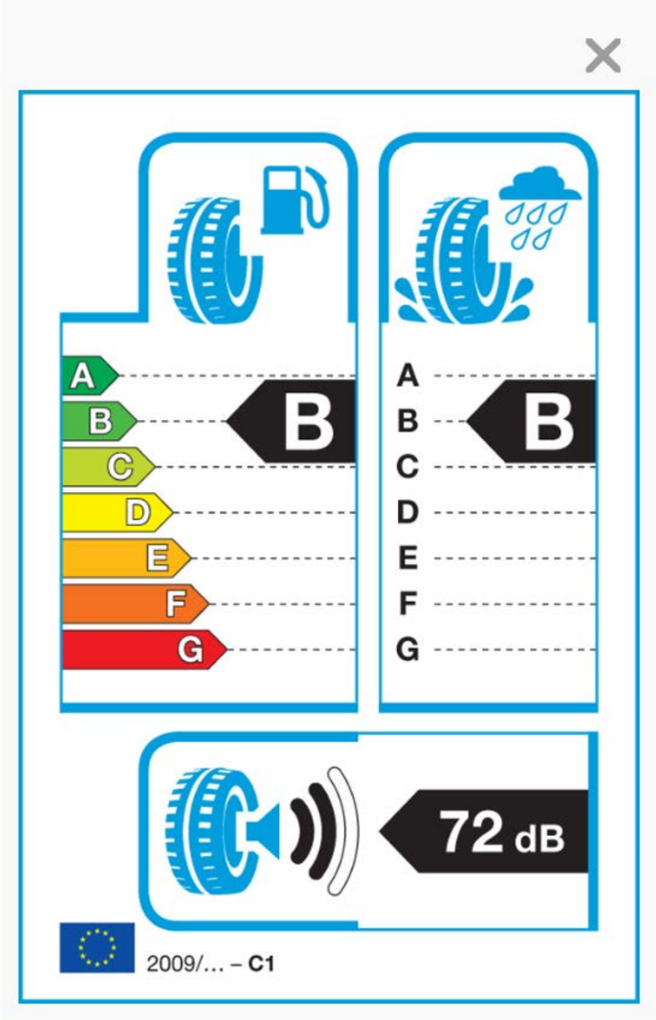
Slide courtesy of Bjarne Schmidt

Measurement methods for rolling resistance properties of road surfaces, B. Schmidt & J. Oddershede, 2016

How can we reduce rolling resistance?

Tyre design

Operated under design conditions



2. Fuel efficiency

Depending on the tire's rolling resistance, its fuel efficiency will range from class A (denoting the best fuel economy) all the way through to class G (delivering the worst fuel economy). Between classes, fuel consumption increases by approximately 0.1 liter for every 100 km driven.

https://www.continental-tires.com/car/tire-knowledge/buying-tires/eu-tire-label

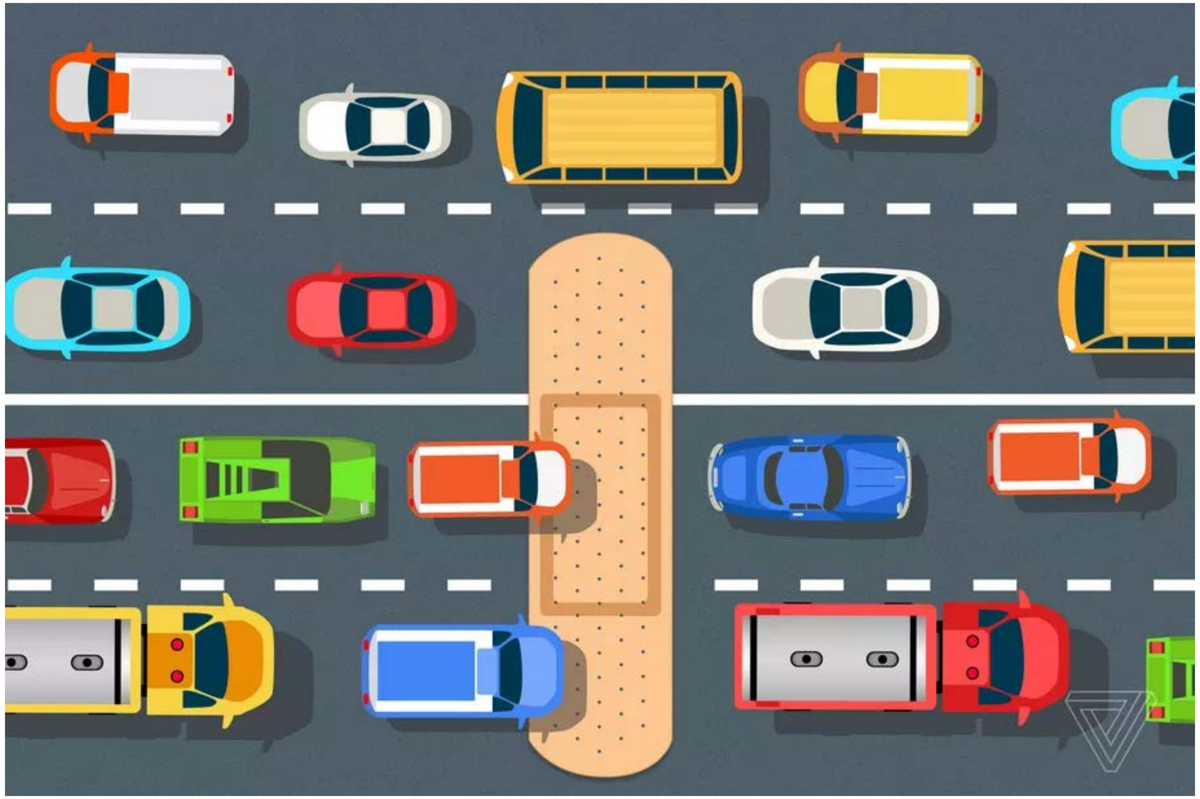
Pavement design

RPUG Road Profile Users' Group

Designed and constructed with the aim of reducing rolling resistance including maintenance strategy

- Road maintenance in general improves pavement surface characteristics and results in a reduction in vehicle CO_2 emissions.

- By applying new surface layers developed and constructed with the aim of lowering rolling resistance, an even greater CO_2 reduction will be achieved- compared to traditional used asphalt pavements



Ref: https://www.theverge.com/2017/5/4/15544156/potholes-self-healing-materials-infrastructure-transportation

Slide courtesy of Bjarne Schmidt

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A well maintained road infrastructure…..

Contributes to a reduction in CO_2 emissions for a competitive price

- Socioeconomic calculations performed by the DRD shows that the cost for obtaining the CO_2 reduction, by using low rolling resistance pavements, are competitive in relation to other CO_2 reducing actions like renewable energy.

- Need to keep in mind:
  - road safety can not be jeopardised as a trade-off for CO_2 emission
  - tire/road noise seems to go hand in hand with rolling resistance.

Slide courtesy of Bjarne Schmidt

Durability & ROI

The key to socioeconomic benefit

- Provide low rolling resistance over entire life time (15+ years)
- Retain grip
- No ravelling or stone loss
- The characteristics of the pavement material must be stable over time (rutting and climatic impact)

Slide courtesy of Bjarne Schmidt

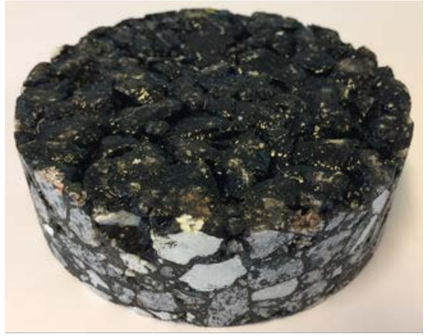
Low rolling resistance pavements

Potential savings

Savings by using low rolling resistance pavement on 50 km of motorways (per year)	
CO_2	3,300 ton
Fuel	1.1 million litre

Total annual CO_2 reduction if all state roads in Denmark consisted of low rolling resistance pavements = 160,000 ton

Traditional Asphalt (SMA 11)

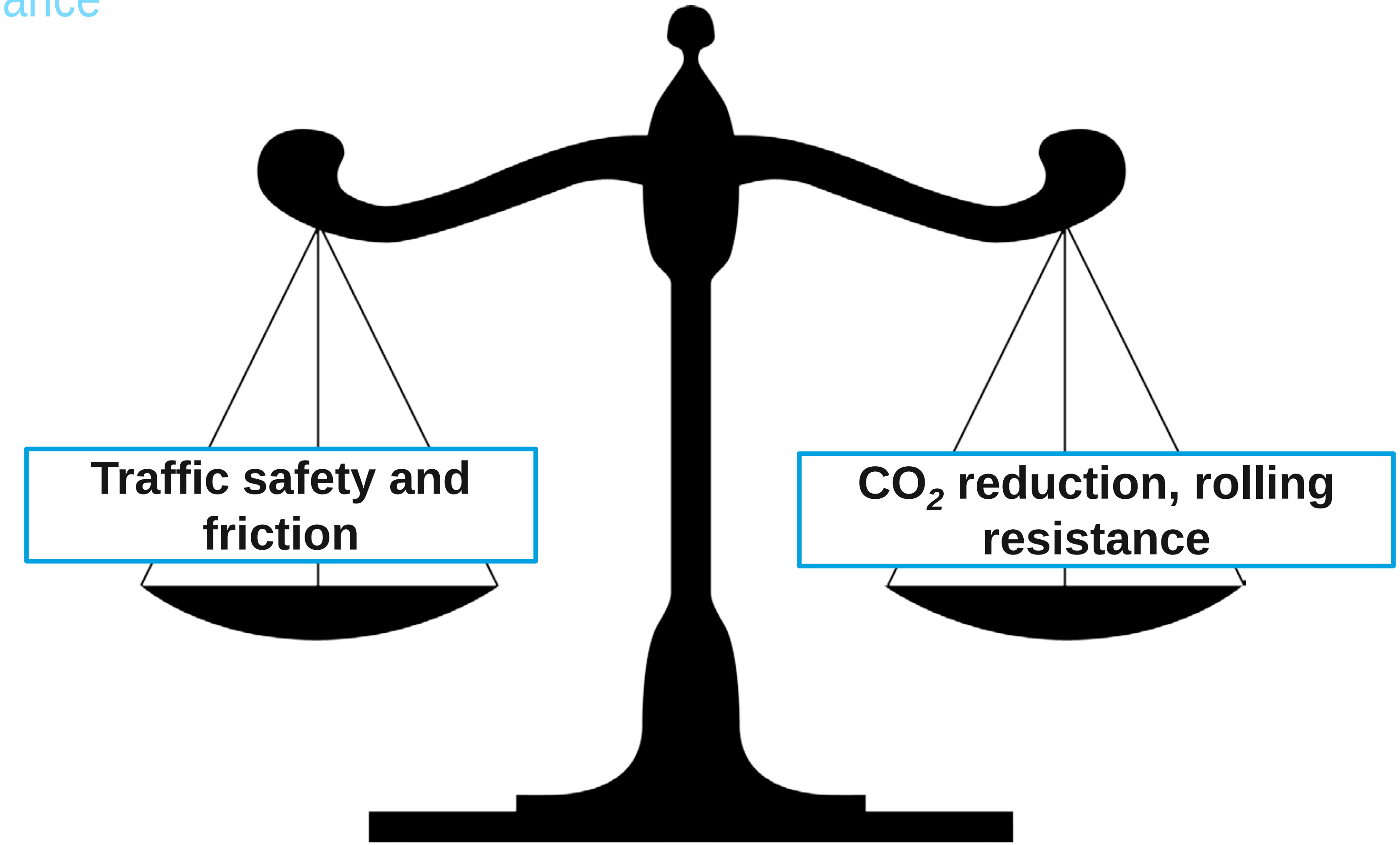


Low rolling resistance asphalt (SMA 8)

Slide courtesy of Bjarne Schmidt

Challenges

Finding the right balance



Slide courtesy of Bjarne Schmidt

What did we learn today?

Rolling resistance

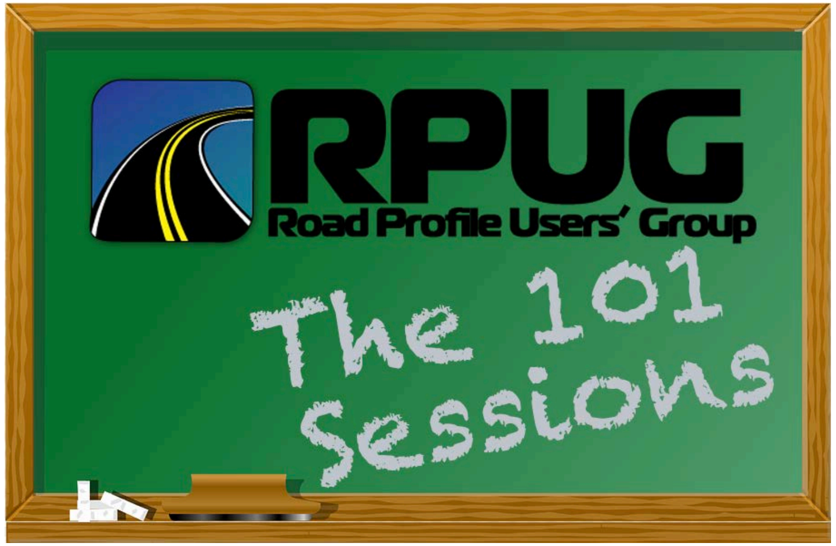
Some take-aways

- 1970s rock bands could have improved touring profits by using fuel efficient tires
- Is responsible for up to 30% of fuel consumption and generates significant levels of CO_2
- Is predominantly caused by deformation of the tire (hysteresis)
- Lower rolling resistance can be achieved through tire and pavement design

Thank you

Provision of materials and expert guidance

- Bjarne Schmidt (ASPL)
- Gerardo Flintsch (VTTI)
- Filippo Giustozzi (RMIT)
- Matteo Pettinari (DRD)



Further information can be found here:

- http://rose-project.dk/news-updates/danish/
- http://miriam-co2.net/

www.gtradial-us.com

QUESTIONS?

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