MIRAVEC

Report on the road infrastructure effects contributing to road vehicle energy consumption and their governing parameters

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MIRAVEC
Modelling Infrastructure Influence on RoAd Vehicle Energy Consumption

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Executive summary

This document describes the different road infrastructure parameters which can contribute to the overall road vehicle energy consumption and highlights those which can be influenced by infrastructure design. It is a report on the effects and parameters that need be considered in order to determine the influence of road infrastructure on road vehicle energy consumption by modelling. The effects and properties were divided into the following five groups:

A. Effects of pavement surface characteristics (rolling resistance, texture, longitudinal and transversal unevenness, cracking, rutting, other surface imperfections)

B. Effects of road design and layout (e.g. road curvature, gradient and crossfall, lane provision)

C. Traffic properties and interaction with the traffic flow (e.g. free flowing traffic vs. stop-and-go, speed limits, access restrictions)

D. Vehicle and tyre characteristics including the potential effect of technological changes in this area

E. Meteorological effects (e.g. temperature, wind, water, snow, ice)

For each effect or property the relevant mechanism or connection to road vehicle energy consumption was described. Based on this analysis the currently available and potential future parameters describing the effect were discussed, followed by an analysis of the potential control that National Road Administrations (NRAs) can be expected to have over these effects. It was found that effects from groups A and B are most likely to be under NRA control, either via road planning and construction or via subsequent monitoring and maintenance. Especially the parameters governing the rolling resistance of pavements are relatively easily accessible data and some of them are already used in modelling together with road alignment parameters. Also the direct measurement of rolling resistance seems to be feasible in the near future. Many effects and parameters from groups C, D, and E are not under the direct control of NRAs, but can be influenced partially or indirectly. Parameters whose effects are difficult to isolate due to the manifold interactions with several phenomena are vehicle speed and temperature.

The necessary data for building models were found to be basically available, even if not always in the required level of detail. For some effects indications were found that new or further developed parameters could substantially improve the prediction capabilities of the models. Knowledge gaps were found concerning the relevance of surface defects and road strength, the influence of road infrastructure features on driving speed, the effects of ITS measures, the degree of adoption of electric vehicles and low rolling resistance tyres and the impact of precipitation on rolling resistance. The introduction of fully electric vehicles is expected to increase the importance of infrastructure-related energy loss mechanisms substantially due to the much higher engine efficiency of electric engines compared to internal combustion engines.

The analysis concluded with recommendations for the subsequent activities in WP2, in which all effects will be evaluated as to which ones are already included in existing models and in which way they are integrated into the model. WP2 will also evaluate the possibility of the addition of new parameters currently not included in the models based on the parameters from WP1. Finally a subset of parameters was recommended for the evaluation of uncertainties in the predictions of existing models.

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1 Introduction to MIRAVEC

CO_2 emissions from road transport represent an important part of the overall greenhouse gas emissions and consequently contribute to the on-going climate change. Efforts to reduce those emissions need to consider all influencing factors on energy consumption of road vehicles, which is directly linked to their carbon footprint. Besides the 'greening' of vehicle technologies the improvement of road infrastructure characteristics related to fuel consumption can contribute to an overall CO_2 reduction in road transport. This requires both a thorough understanding of those interactions and the implementation of results in current pavement and asset management practice. In contributing to both objectives MIRAVEC enables National Road Administrations (NRAs) to effectively support the reduction of road transport greenhouse gas emissions.

While some previous and on-going projects like ECRPD[1] or MIRIAM[2] focused on specific topics in this area, the objective of MIRAVEC is to build on existing knowledge and models. In doing so MIRAVEC aims at achieving a more holistic view considering a broad variety of effects (e.g. the interaction between road design and traffic flow). Moreover, MIRAVEC will investigate the capabilities of available models and tools and evaluate the relative importance of different road infrastructure characteristics for different settings (e.g. topography or network type). The relationship with road safety and noise emissions will be examined. The project results will be compiled into recommendations to NRAs on how to implement the findings, models and tools in pavement and asset management systems. The dissemination to the NRAs is planned by using workshops, project presentations and a project website.

1.1 Objectives of Work Package 1

Work Package 1 (WP1) will identify the most important effects contributing to road vehicle energy consumption which are governed by interaction with the infrastructure and their associated parameters. This work package will create a compilation of effects and parameters which will serve as a basis for the detailed work plans of Work Package 2 and 3.

1.2 Structure of Work Package 1

This work package focuses on describing and evaluating the phenomena influencing road vehicle energy consumption and highlighting those which are due to pavement characteristics or road design and their influence on the traffic flow. It will be led by AIT, assisted by the other partners, using their experience and wide range of expertise to achieve a comprehensive view of the subject.

1.2.1 Task 1.1: Infrastructure effects contributing to vehicle energy consumption

This task aims at evaluating the different contributions to the overall road vehicle energy consumption with a view to extracting those which can be influenced by infrastructure design. Special attention has been given to the following effects:

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[1] ECRPD - Energy Conservation in Road Pavement Design, Maintenance and Utilisation

[2] MIRIAM - Models for rolling resistance In Road Infrastructure Asset Management Systems

A. Pavement surface characteristics (rolling resistance, texture, longitudinal and transversal unevenness, cracking, rutting, other surface imperfections)
B. Road design and layout (overall design standards, road trajectories, inclination and crossfall, alignment, design speed, lane provision)
C. Traffic properties and interaction with the traffic flow (tolerance of congestion, speed limits, access restrictions)
D. Potential effects of current trends in vehicle and tyre development (as far as interaction with the infrastructure is concerned)

Interactions and synergies between different effects that can occur are described. A fifth group covering meteorological effects has been added as a result of WP1 work.

1.2.2 Task 1.2: Parameters describing road infrastructure effects

Using the results of task 1.1 the governing parameters for each of the listed effects have been determined to enable quantitative evaluations. The existing knowledge on those parameters was evaluated along with the available measurement methods. The proposed parameters need to be relevant for the effects to be described, which may in some cases entail a choice between different parameter sets.

1.2.3 Task 1.3: Compilation of a comprehensive overview

The results of Tasks 1.1 and 1.2 has been used to compile this report on the effects and parameters that need be considered in order to determine the influence of road infrastructure on road vehicle energy consumption. This report includes an investigation of the phenomena, a list of requirements for the models of WP2 as well as a description of knowledge gaps.

2 Inventory of potential infrastructure related effects

2.1 Components of road vehicle fuel consumption

Road vehicles use the energy provided to them in the form of combustible fuel to power the engine and redistribute the generated mechanical energy to several components.

From a single vehicle point of view, the following resistances and energy loss mechanisms have to be overcome to achieve propulsion:

1) Rolling resistance
2) Air resistance
3) Inertial resistance (in the case of acceleration/deceleration)
4) Longitudinal gradient resistance
5) Side force resistance
6) Engine losses
7) Transmission losses
8) Losses from the use of auxiliaries.

The relevant forces opposed to propulsion active at the drive axle can consequently be summarised as follows:

$$F = F_{roll} + F_{air} + F_{inertial} + F_{gradient} + F_{side}$$

With

F_{roll}	Rolling resistance
F_{air}	Air resistance
$F_{inertial}$	Inertial resistance
$F_{gradient}$	Gradient resistance
F_{side}	Side force resistance

Figure 1 shows an example for energy flows in a passenger car with an internal combustion engine.

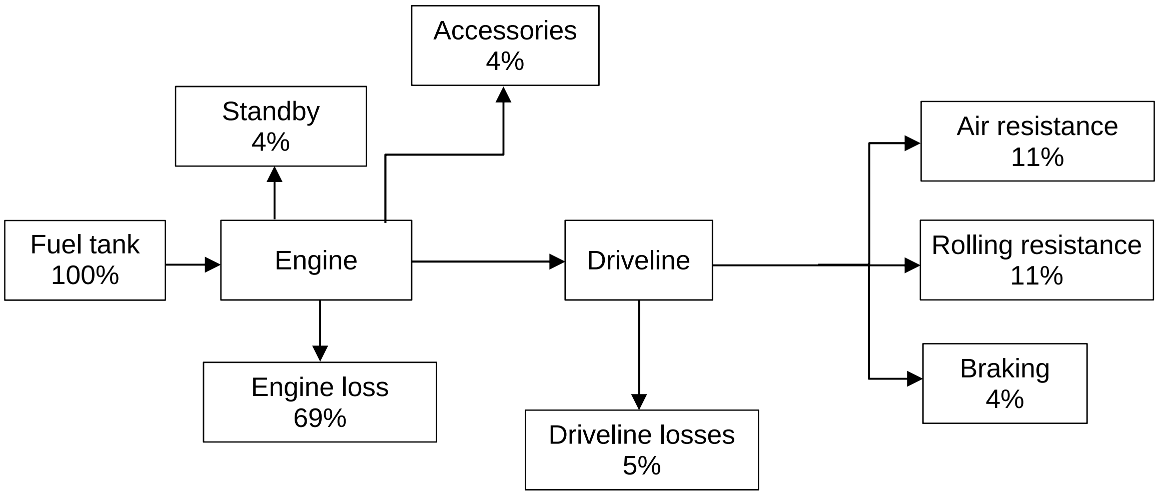


Figure 1: Energy flows in a typical passenger car for highway driving (from [1])

As can be seen from Figure 1 engine losses including standby can use up more than 70% of the fuel energy in the case of highway driving, corresponding to an engine efficiency of about 30%. A small amount of approximately 2% is used for accessories, while only 25% of the fuel energy arrives at the driveline. Driveline losses use up another 5%, which leaves about 20%, 18% of which are used to overcome rolling resistance and air resistance, while the rest is lost in braking. This example is representative for a driving speed in the range of 70-90 km/h (see e.g. [23]). For higher speeds, the share of losses due to air resistance increases further.

This means that a considerable amount of energy is consumed by the operation of the vehicle itself and that only a relatively small fraction is available for actual propulsion. The choice of gear and vehicle speed will have a major impact on fuel consumption, because they directly influence the internal components of the vehicle.

Interaction with the road infrastructure will mainly influence the rolling losses if a constant speed is assumed. However, if the road infrastructure does also influence the choice of speed its impact will be much higher. Therefore it is necessary to distinguish between different types of infrastructure influence, ranging from direct effects of the pavement to influencing e.g. relevant components of the driver behaviour like the choice of speed.

The importance of infrastructure-related effects like rolling resistance is expected to increase considerably with the introduction of fully electric vehicles, where engine efficiencies between 60% and 95% are possible, compared to the maximum currently achievable engine efficiencies of internal combustion engines of up to 45%. For a detailed discussion, see section 2.6.1.

2.2 Overview of effects

In this report effects with a verified or potential effect on road vehicle fuel consumption will be analysed. Special attention will be paid to effects connected with the built road infrastructure. The effects of changing the modal split, i.e. the reduction of road traffic volumes by diverting transport activities to other modes of transport will not be considered. The intention is to consider a broad range of effects before more detailed analyses of only those phenomena which can be influenced by NRAs are performed at later stages within the project.

The investigated effects can be categorised into the following groups A to E:

A. Effects of pavement surface characteristics (rolling resistance, texture, longitudinal and transversal unevenness, cracking, rutting, other surface imperfections)
B. Effects of road design and layout (overall design standards, road trajectories, gradient and crossfall, lane provision)
C. Traffic properties and interaction with the traffic flow (e.g. free flowing traffic vs. stop-and-go, speed limits, access restrictions)
D. Vehicle and tyre characteristics including the potential effect of technological changes in this area
E. Meteorological effects (e.g. temperature, wind, water, snow, ice)

The groups have been chosen because the effects in each of the groups share certain common characteristics.

The effects of **Group A** are closely connected to properties of the pavement itself and its geometrical and mechanical properties. These properties are typically determined in the process of pavement design and will be subject to approval testing and monitoring. Most pavement properties in this group can be controlled and changed via pavement maintenance which can include activities from surface texture improvements or small crack repairs to complete repaving. This means that these properties and their associated effects can be changed more easily and within a shorter timeframe that those of group B. Management of pavement properties is typically under the direct control on National Road Administrations (NRAs). If the associated pavement parameters are accessible to regular monitoring, it should also be possible in the future to include the impact of the pavement on road vehicle fuel consumption into pavement management systems and maintenance planning.

Group B contains road infrastructure properties and their effects which are connected to general road layout and road trajectory. These properties are typically determined in the planning and construction phase of the road and are often fixed during the working life of the road. Changing these parameters would typically require at least partial demolition and rebuilding of the road. While these properties are typically under the control of the NRAs, all alternatives and modifications should be considered in the planning and construction phase to avoid high costs.

Group C includes properties of the road traffic itself, like traffic volume, average speed, composition or traffic flow. These are important basic parameters which will also determine the potential of other effects. Pavement rolling resistance for example is different for passenger cars and heavy goods vehicles (HGVs), which means that the share of HGVs in the overall traffic will determine the potential effects of changing the pavement rolling resistance. This group also contains road infrastructure components which interact with the traffic flow in a way that can lead to changes in the fuel consumption. The control of NRAs over these properties and effects is exerted via traffic control measures.

The effects and properties in **Group D** comprise the characteristics of vehicles and tyres, which play an important role in determining the fuel consumption of the individual vehicle. These are mainly determined by developments in vehicle technology, consumer demands and legislation. The influence of NRAs on the vehicle properties is limited and mostly indirect, e.g. in the form of access restrictions, priority lanes, differentiated tolls or speed limits for specific vehicle classes. Due to the fact that a large share of vehicle energy losses are determined by vehicle and tyre properties, research and development aiming at vehicle fuel consumption reduction has so far mainly concentrated on this field.

Group E contains meteorological effects with a potential influence on road vehicle energy consumption. Typical parameters are temperature and wind speeds, as well as the presence of water, ice and snow on the pavement surface. Some of these parameters can have an important modifying effect on phenomena from other groups, like rolling resistance and aerodynamic resistance. Options for NRA influence are for example the use of road surfaces that facilitate the drainage of water or the removal of snow and ice, or the design of infrastructure layout which takes prevailing wind directions into account to avoid increasing the air resistance.

2.3 Group A: Effects of Pavement surface characteristics

2.3.1 Rolling resistance of pavements

Description of the mechanism

Rolling resistance is an energy loss mechanism due to the deformation of the rolling tyre by the contact with the road surface. The pressure distribution in a rolling rubber tyre is non-symmetric, with higher forces concentrated in front of the tyre centre. This leads to a torque acting against the rotation of the tyre, which effectively results in a force opposing vehicle propulsion (Figure 2). The tyre deformation generally follows a hysteresis curve which means that the deformation creates heat energy which is lost for the purpose of propulsion. The magnitude of this deformation depends on the mechanical properties of the tyre, the geometrical features of the road surface and the speed of the vehicle. The effect of pavement surface deflection is analysed in section 2.3.6.

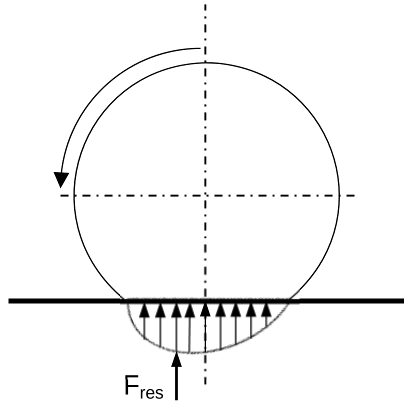


Figure 2: Contact pressure distribution and resulting force in a tyre rolling on a pavement

This section will focus on the pavement contribution to rolling resistance. The features of the road surface which influence the rolling resistance are road surface irregularities in the macro- and megatexture and unevenness range (see Figure 3).

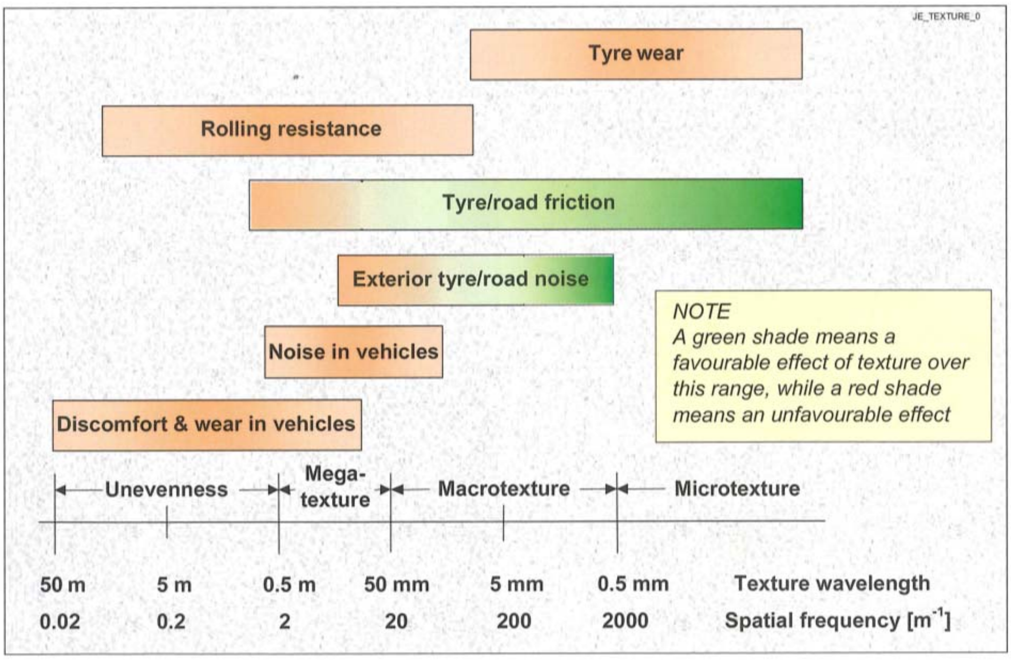


Figure 3: Texture and unevenness wavelengths and spatial frequencies with the most significant anticipated effects (from [2])

The effect of the pavement on rolling resistance has been investigated e.g. in [3], the ECRPD [4], MIRIAM [5], COOEE[3] [6] and TYROSAFE[4] [7] projects.

Associated parameter

The rolling resistance of tyres is typically determined as a tyre-specific property by testing on a steel drum according to ISO 28580 [8]. However, this is a highly artificial setting and was mainly chosen due to the need to tightly control all testing parameters. The resulting values characterize the tyre itself, but cannot be used to make a statement about the pavement influence on rolling resistance. Rolling resistance on a real road surface can be measured using one of the following methods:

a) Force or torque measurements in specialized trailers
b) Force or torque measurements in the wheel suspension or transmission
c) Coast-down measurements of vehicles including precise measurements of the (negative) acceleration
d) Measurements on drums fitted with a replica road surface
e) Fuel consumption measurements in closely controlled drive cycles

Methods a) and b) are in principle suitable for rolling resistance monitoring of pavements for longer road sections. The MIRIAM project has compared rolling resistance trailers from Germany, Poland and Belgium and has concluded that although the principle is promising further development is needed [9].

The rolling resistance force F_{roll} depends on the tyre load and weight and is expressed as a rolling resistance coefficient C_R by relating it to the force component F_Z normal to the pavement, which is pressing the tyre against the pavement surface:

$$F_{roll} = C_R F_z$$

The differences in rolling resistance induced by different pavement types can be measured if all other influencing parameters can be kept sufficiently constant or are accounted for. These include e.g. tyre type, tyre loads and pressures, temperatures, gradients, or wind speed.

Formulas for the determination of rolling resistance from other road surface properties typically take the following form:

$$C_R = C_R(MPD, IRI, v, \ldots)$$

One possible model has been used in the ECRPD project [4]:

$$F_{roll} = m \cdot \left(\eta_0 + \eta_1 \cdot (25 - T) + \mu_0 \cdot MPD + \mu_1 \cdot v \cdot MPD + \lambda_0 \cdot IRI + \lambda_1 \cdot v \cdot IRI\right) \tag{3.9}$$

where

MPD is the macrotexture measure [mm]
IRI is the road roughness measure [mm/m]
m is the vehicle mass [kg]
v is the velocity [m/s]
T is the air temperature [°C]
$\eta_0, \mu_0, \mu_1, \lambda_0, \lambda_1$ are constant coefficients

[3] COOEE - CO_2 emission reduction by exploitation of rolling resistance modelling of pavements
[4] TYROSAFE - Tyre and Road Surface Optimisation for Skid resistance and Further Effects

Options for NRA influence

Currently rolling resistance cannot be controlled directly by NRAs, as there is no standardized method for determining the pavement contribution to rolling resistance. However, currently on-going projects like MIRIAM and COOEE are looking into the possibilities of using trailers for the monitoring of rolling resistance as a road surface property in analogy to skid resistance or noise emission. When a trailer-based rolling resistance measurement method is sufficiently well developed to be standardized, it could be used to provide the data basis for introducing rolling resistance into pavement management and maintenance. However, this requires a substantial amount of additional measurements. If the dependence of rolling resistance on texture and unevenness parameters is sufficiently well understood, rolling resistance may be controlled by managing these primary pavement properties and relying on validated models to calculate the rolling resistance and fuel consumption impact from these parameters.

2.3.2 Texture

Description of the mechanism

The texture of a pavement is defined as the deviation of the pavement surface from a true planar surface within certain specified spatial wavelength ranges. EN ISO 13473-1 [*10*] defines the following ranges:

- Microtexture: Deviations of the pavement surface from a true planar surface with a spatial wavelength of less than 0.5 mm. These surface structures are typically smaller than both tyre tread features and pavement aggregate grain sizes.
- Macrotexture: Deviations of the pavement surface from a true planar surface with a spatial wavelength between 0.5 mm and 50 mm. These surface structures are in the size range of tyre tread features.
- Megatexture: Deviations of the pavement surface from a true planar surface with a spatial wavelength between 50 mm and 500 mm. These surface structures are comparable in size to the tyres and wheels themselves.
- Unevenness: Deviations of the pavement surface from a true planar surface with a spatial wavelength above 500 mm. These types of deviations are analysed in 2.3.3.

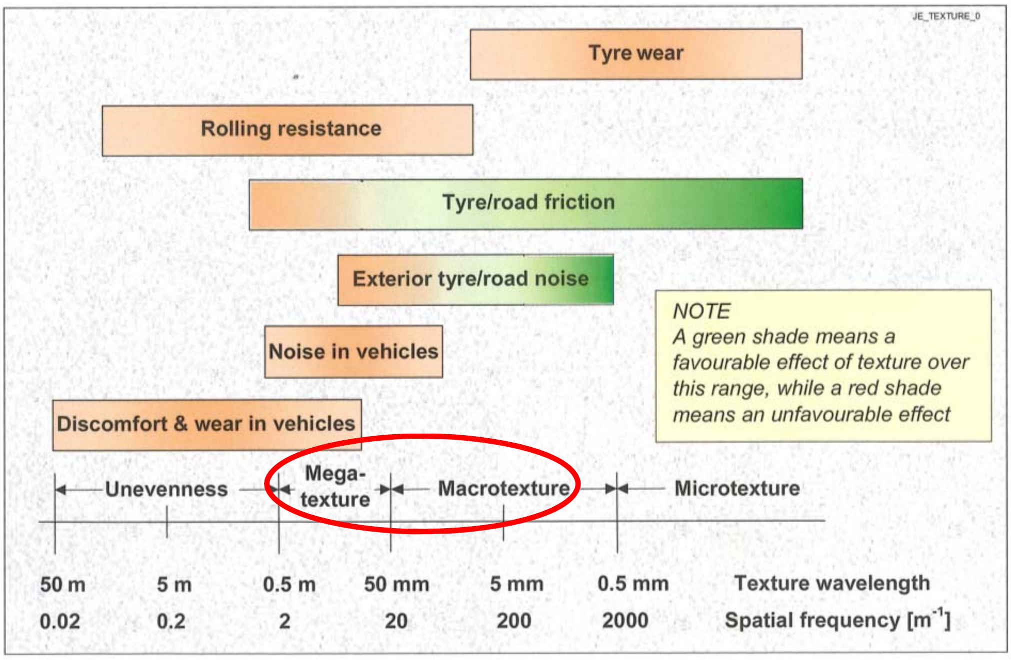


Figure 4: Macro- and megatexture wavelengths (from [2])

The interesting texture wavelength ranges which contribute to a deformation of the tyre and induce rolling resistance losses are mainly in the macro- and megatexture range. Texture parameters can be used in modelling rolling resistance and other surface parameters. In principle texture measurements have the potential to substitute the direct measurement of several road surface properties like rolling resistance, skid resistance or noise emission if sufficiently accurate models were available. Texture measurements are typically easier to perform than the specific measurements for these individual properties, and some NRAs already include them in their pavement monitoring.

Associated parameter

The ISO 13473-n series of standards covers the measurement of pavement texture with profilometers and associated indices. All indices are based on filtered longitudinal height profiles of the pavement surface typically recorded with a mobile or stationary laser profilometer.

Figure 5: The texture measurement device as part of the Austrian RoadSTAR road and pavement monitoring vehicle, which also performs measurements of skid resistance, longitudinal and transversal evenness

EN 13036-1 [12] specifies the simpler, but more unreliable sand patch test, which yields less information and is more common in the low-level road networks. The most commonly used parameter is the MPD (mean profile depth) defined in ISO 13473-1 [*10*] for an evaluation length of 100 mm (see Figure *6*). It is designed to indicate the typical elevation of profile peaks above an average profile baseline.

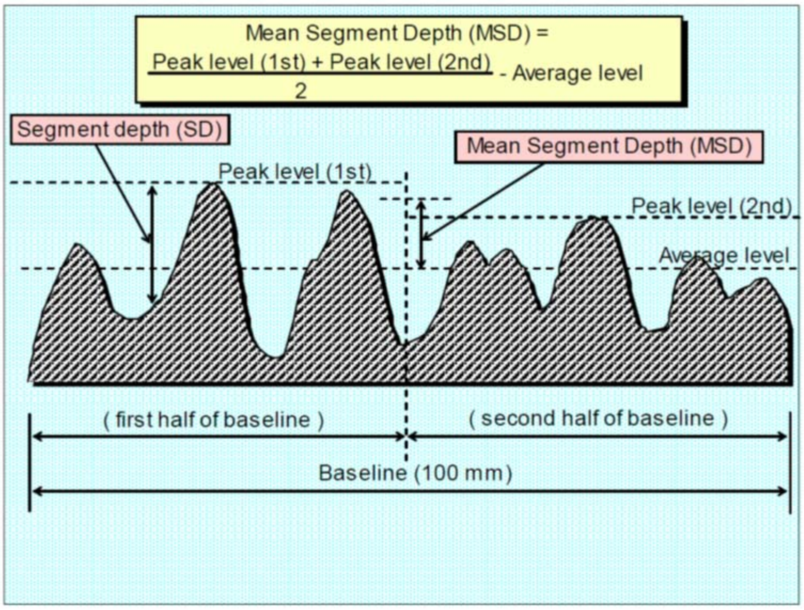


Figure 6: Derivation of the MPD (which is equal to MSD) from texture profiles (from [2])

As such it gives a certain indication of the possible penetration depth of tyre features, but can also be used to ensure sufficient skid resistance and surface drainage. Other methods for analysis in the macro- and megatexture ranges are based on the spectral analysis of the profiles (Figure 7).

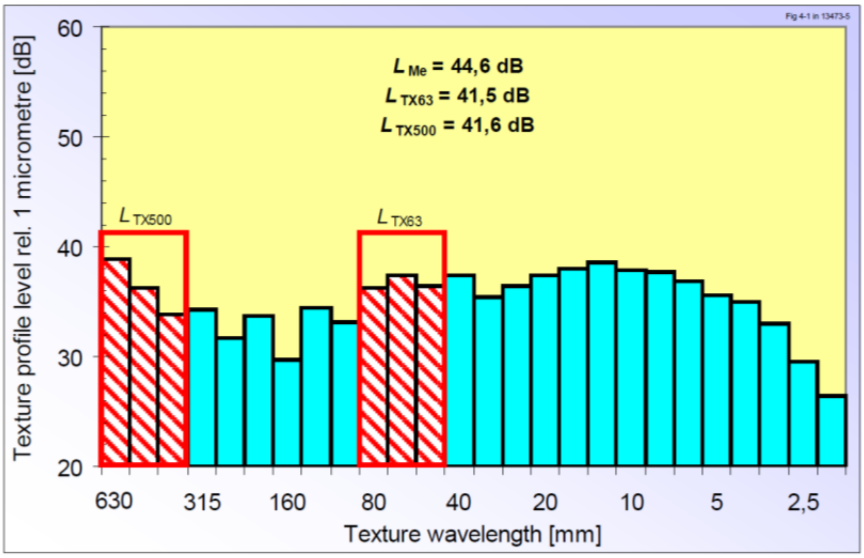


Figure 7: Example of spectral texture analysis using one-third octave bands (from [2])

The correlation of road texture profiles to rolling resistance can be improved by enveloping the texture profiles (Figure 8), which highlights the fact that tyres will not fully penetrate into the texture profile.

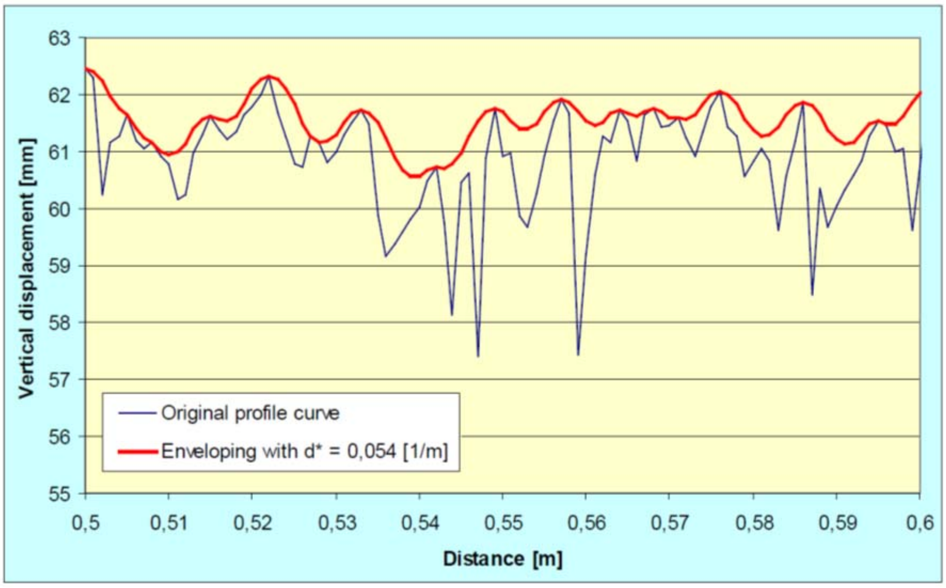


Figure 8: Enveloping of a texture profile to simulate the limited penetration depth of tyres (from [5])

The investigation of this technique in the MIRIAM project [5] has shown a marked increase in the correlation of MPD calculated from an enveloped profile with the rolling resistance coefficient C_R compared to correlation analysis performed without enveloping. Further investigation in this direction could yield texture parameters which have even more significance for rolling resistance.

The MPD is also the texture parameter most frequently used for modelling rolling resistance (see [*4*] and 2.3.1) and pavement influence on vehicle fuel consumption. Figure 9 shows an example of modelling the impact of changes in MPD on fuel consumption, which was found to be 2.8% per unit of MPD in the presented case (IRI=1, v=90 km/h).

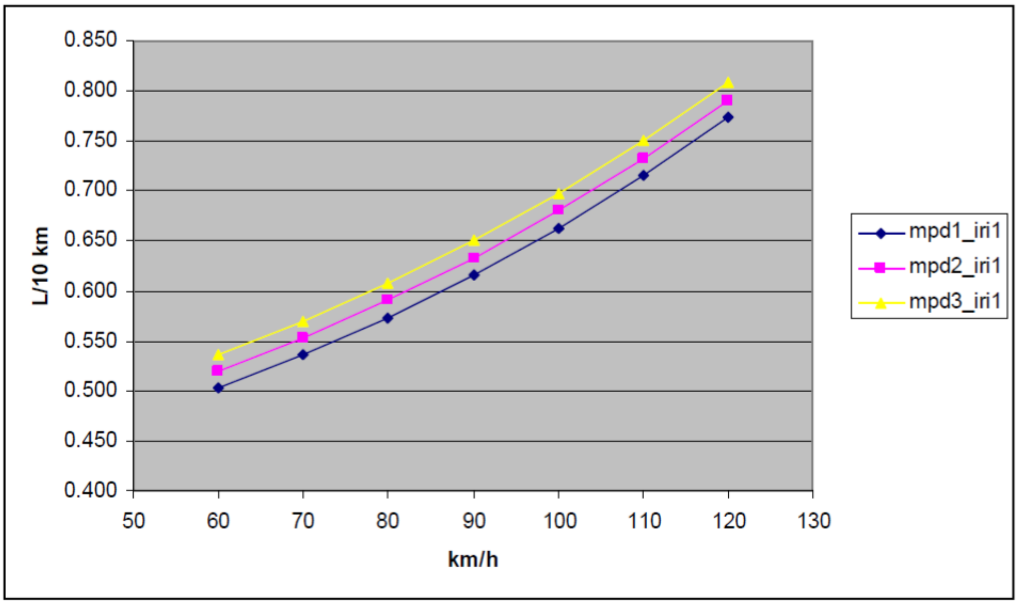


Figure 9: Modelling of changes in passenger car fuel consumption with MPD (MPD = 1,2,3 mm) in VETO (from [13])

Options for NRA influence

The macro- and megatexture of pavements is controlled in the construction phase to ensure sufficient skid resistance and surface drainage. Insufficient surface texture can lead to retexturing or other surface treatments for safety reasons. Measurements of MPD are the most commonly available data for texture. As the measurement of texture profiles with laser profilometers is technically similar to the measurement of longitudinal and transversal evenness, it is to be expected that texture measurements will be included in standard pavement monitoring procedures to an increasing degree. Controlling pavement texture may become the key tool to managing pavement surface properties for NRAs.

2.3.3 Longitudinal unevenness

Description of the mechanism

Longitudinal unevenness is defined as deviations from an ideally flat road surface in the range of spatial wavelengths between 0.5 m and 50 m (Figure 10).

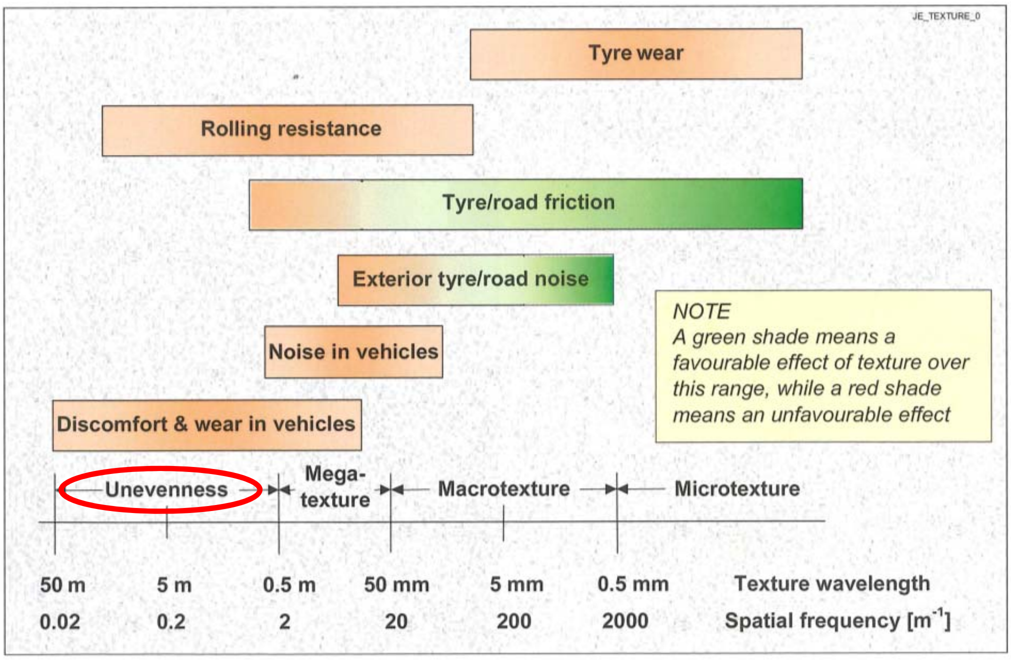


Figure 10: Longitudinal unevenness wavelengths (from [2])

Longitudinal unevenness is an important parameter for the ride comfort on road pavements. It contributes to the overall road vehicle energy consumption via three mechanisms:

1) The longitudinal unevenness of pavements contributes to the rolling resistance of the tyre, albeit to a smaller degree than texture.
2) Longitudinal unevenness induces vibrations in the wheel suspensions. These vibrations have to be dampened to ensure ride comfort, which results in a conversion of mechanical energy into heat energy.
3) High levels of longitudinal unevenness will induce drivers to reduce the vehicle speed.

The first effect is described in section 2.3.1 in the general rolling resistance model. It has to be noted that this direct effect on rolling resistance is considerably smaller than the effect of texture. This is to be expected due to the long wavelengths involved, which correspond to movements of larger sections of the whole vehicle than tyre tread elements. The second effect is due to the necessity of protecting the car occupants from experiencing discomfort. Therefore the induced vertical oscillations have to be dampened, which leads to energy conversion into heat. This effect needs to be taken into account when modelling the energy consumption of the whole car. An investigation of this effect is presented in [14], which indicates substantial differences between roads with low and high unevenness. It is not always considered to be part of the rolling resistance, and is not always modelled separately. The third effect works indirectly via influencing the driver behaviour (see section 2.5.5). Investigations in [13] show that it is necessary to include this effect of unevenness to achieve a complete picture.

Associated parameter

Longitudinal unevenness of pavements is closely related to ride comfort and is therefore a key parameter in pavement management. The relevant European standard EN 13036-5 [15] specifies the measurement of longitudinal unevenness and the calculation of unevenness indices. It requires the measurement of a longitudinal road height profile with a sampling interval of 0.05 m. This profile is the basis for the calculation of different possible unevenness indices. The most common index is the IRI (International Roughness Index), which is intended to represent the reaction of a specific quarter-car model (golden car) to the road profile (Figure 11). The quarter-car model of the golden car includes a wheel with a tyre, a suspension spring with vibration dampener and the associated masses.

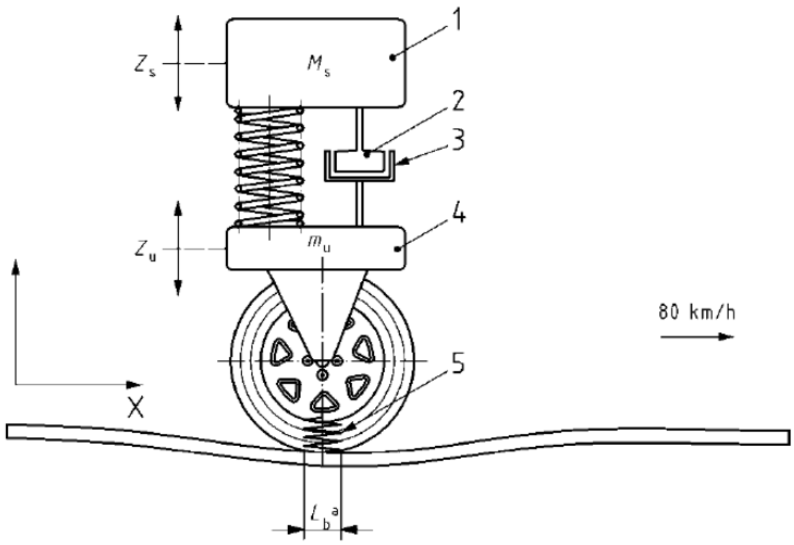


Figure 11: Golden Car model for the determination of the IRI (from [15])

IRI values are given as m/km. The IRI includes transfer functions representing the action of a suspension system; however, it is mainly designed as a measure for ride comfort.

The IRI is used for modelling the unevenness impact on vehicle fuel consumption (see [*4*] and 2.3.1). Figure 12 and Figure 13 show an examples of modelling the impact of changes in IRI on fuel consumption, which was found to be 0.8% per unit of IRI for a passenger car and 1.3% per unit of IRI for a truck (v=90 km/h in both cases).

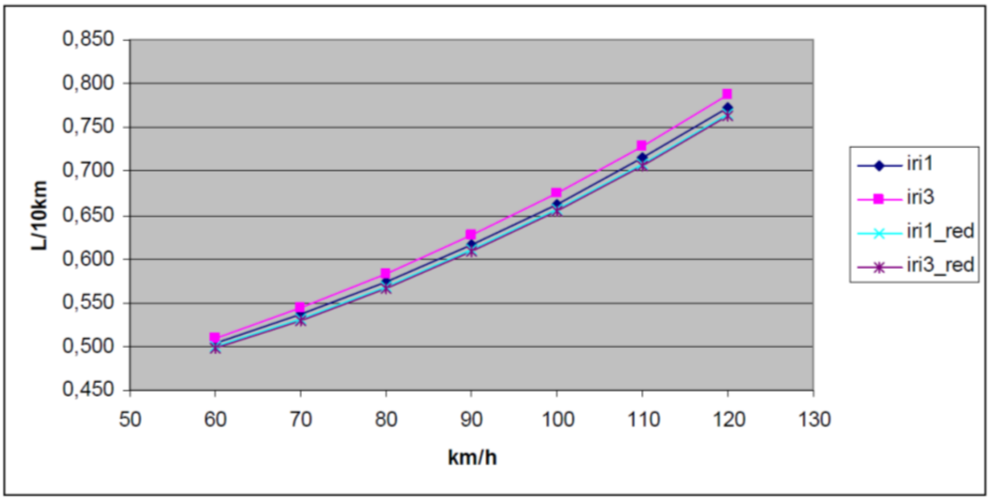


Figure 12: Modelling of changes in passenger car fuel consumption with IRI (IRI = 1,3) with (_red) and without IRI speed effect in VETO (from [13])

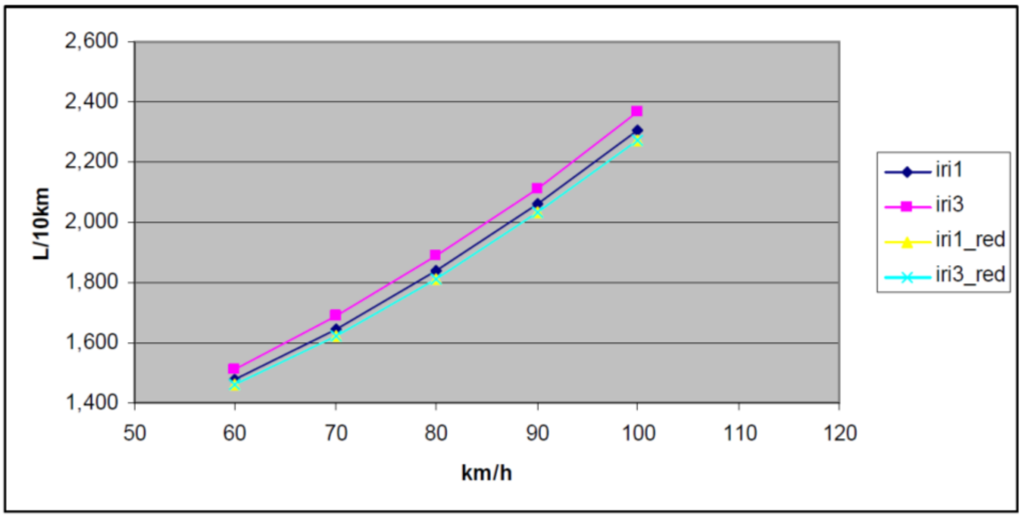


Figure 13: Modelling of changes in truck fuel consumption with IRI (IRI = 1,3) with (_red) and without IRI speed effect in VETO (from [13])

The IRI is not the only possible unevenness index. Other indices have been proposed, which rely on a spectral analysis of the longitudinal height profile, like the weighted longitudinal profile [16] (see Figure 14 and Figure 15). These parameters are intended to better distinguish between single irregularities, general unevenness and periodic unevenness. Their usefulness for road vehicle energy consumption modelling remains to be investigated.

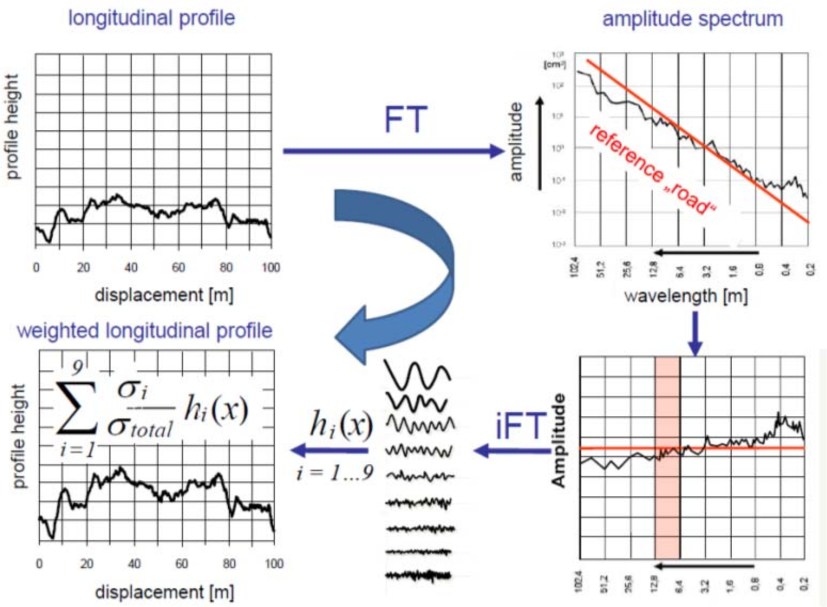


Figure 14: Calculation scheme for the Weighted Longitudinal Profile (WLP) (from [16])

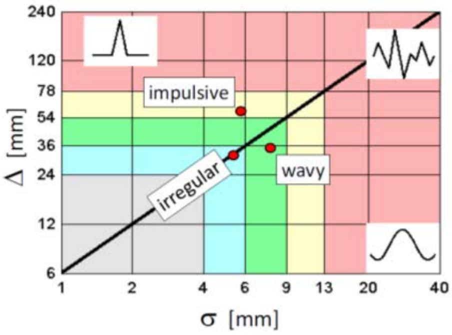


Figure 15: Evaluation scheme for the Weighted Longitudinal Profile (WLP) (from [16])

Options for NRA influence

The longitudinal unevenness of pavements is a key performance parameter in the high-level road network and is typically subject to approval testing and monitoring. NRAs already seek to control longitudinal evenness for the purposes of ensuring ride comfort, which gives them a rather large influence on this parameter. This also leads to considerable available data concerning longitudinal unevenness, which can form a basis for fuel consumption modelling. However, these data would need to be supplemented with texture measurements due to the higher influence of texture on fuel consumption.

2.3.4 Transversal unevenness

Description of the mechanism

In addition to the its intentionally designed crossfall, the road surface will also exhibit deviations from this ideal transversal profile in the form of ruts, steps, ridges, bumps and edge slumps (Figure 16). Ruts typically form in the wheel paths as a result of the action of the wheels on the pavement material.

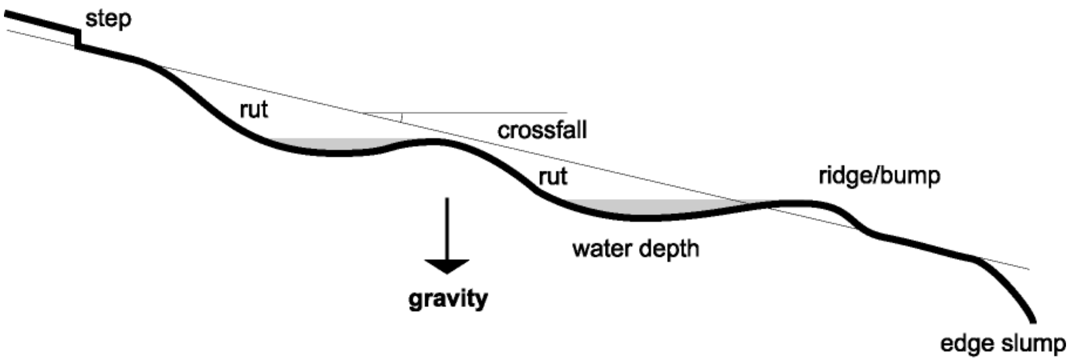


Figure 16: Crossfall and transversal unevenness features

Both crossfall and transversal unevenness have the potential to induce an increase in vehicle fuel consumption. Transversal unevenness can act similar to longitudinal unevenness by inducing increased tyre deformation and suspension losses. This will especially be true if the lateral position of transversal unevenness features changes considerably, which either introduces additional encountered longitudinal unevenness or the need for frequent steering corrections. Transversal unevenness does also have a similar effect on driving speed as longitudinal unevenness, inducing drivers to reduce speed with increasing transversal unevenness.

In addition to that, water accumulation in the ruts can lead to insufficient drainage and impact road safety negatively. When driving in the ruts, the rolling resistance can increase due to the energy required to displace the water (see 2.7.3).

Associated parameter

The measurement of transversal unevenness is defined in EN 13036-6 [17] and EN 13036-8 [18]. While no specific measurement device is prescribed, typically a straightedge or a laser profilometer is used. The parameters used to describe the transversal unevenness are the rut depth, the height of the different irregularities and the theoretical water film depth for water accumulating in the ruts. These parameters are typically determined every 5 to 10 m and averaged for longer intervals of e.g. 100 m. Crossfall and rut depth typically constitute the major deviations from an ideal horizontal road surface and are therefore the best candidates for the inclusion in models. The main parameter used for transversal unevenness is average or maximum rut depth.

Rut depth can be included in modelling. Investigations based on the VETO model in [13] show that transversal unevenness contributes to the speed effect of longitudinal unevenness.

Options for NRA influence

Transversal unevenness is monitored during the lifetime of pavements for safety reasons. For this reason, sufficient data for modelling should be available. The development of deep ruts can typically require maintenance actions like a repaving which would then also reduce the negative impact on fuel consumption. The level of control that can be exerted by NRAs on this parameter is high.

2.3.5 Joints and surface defects

Description of the mechanism

The presence of surface irregularities like joints or surface defects like cracks, ravelling, potholes, loss of material may introduce additional features of longitudinal and transversal unevenness as well as texture. This means that the impacts on fuel consumption can in general be described by the parameters associated with these surface properties. However, in the case of severely damaged surfaces there may be additional energy dissipation. These types of surfaces will in general have to undergo maintenance for safety reasons in any case.

Associated parameter

In addition to the already mentioned parameters for longitudinal and transversal unevenness an area or longitudinal density of surface defects could be defined. This would include the identification and classification of relevant surface defects in the course of already performed crack detection surveys. The classification would have to take the predicted impact of the identified type of surface defect on fuel consumption onto account and determine the number of these defects per unit area or per km of road length. This can then be converted into an indicator for the predicted additional fuel consumption.

Options for NRA influence

NRAs control and monitor the occurrence of surface defects and will typically start maintenance activities for safety reasons before the impact on fuel consumption would require an additional parameter.

2.3.6 Road strength and bearing capacity

Description of the mechanism

In the tyre-road contact zone the road surface will be deformed as well as the tyre. If the pavement material exhibits a hysteresis, energy will be lost. It is in principle to be expected that this effect is larger for flexible pavements than for rigid pavements. The details of this effect will depend on the layer structure of the pavement. However, the energy dissipated in the tyre deformation was found to be substantially larger than that of the pavement deformation in [19].

Associated parameter

The bearing capacity of pavements, which is a measure of the road strength, can be measured with a falling weight deflectometer (FWD), deflectograph and other devices. Measured deflection can be used as a parameter for correlation with rolling resistance.

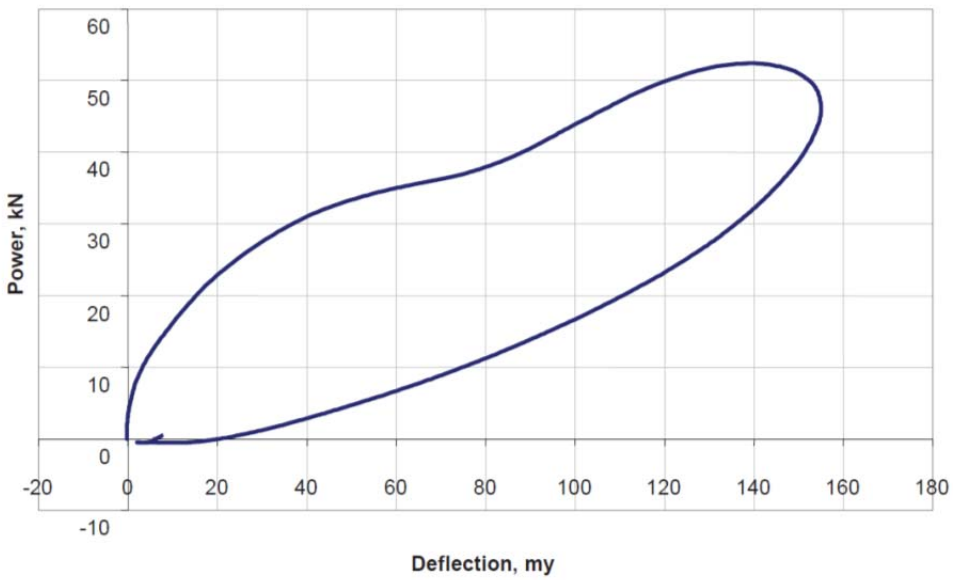


Figure 17: Typical hysteresis curve of a FWD test (from [19])

The energy loss through pavement deformation can be calculated as the area of the hysteresis curve shown in Figure *17*. The research presented in [19] compared the deformation of the road pavements as measured by FWD to the effects of rolling resistance. However it was found, that rolling resistance due to pavement deformation was only a few percent of the overall rolling resistance, which is a much lower impact that the effect of e.g. texture. If very accurate models will be available in the future, they may have to take this effect into account at least for very weak road pavements.

Options for NRA influence

Bearing capacity is a basic pavement design parameter and is determined by the layer structure of the pavement and the materials used in the construction. NRAs will control it during planning and construction and can influence it through pavement maintenance measures. It can be checked with a FWD test.

2.4 Group B: Effects of road design and layout

2.4.1 Vertical alignment (gradients)

Description of the mechanism

The vertical inclination of roads in the direction of travel plays an important role in determining the fuel consumption. Longitudinal gradients lead to a force component of gravity either in the direction of travel or opposed to it (Figure *18*).

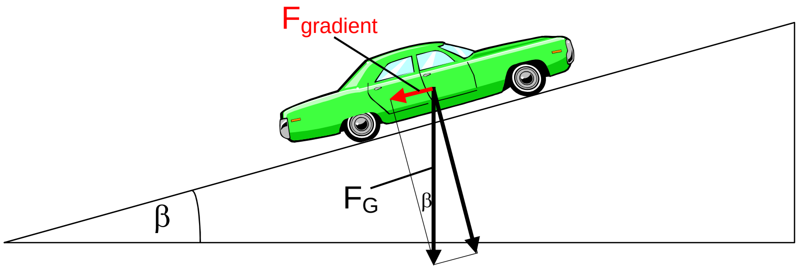


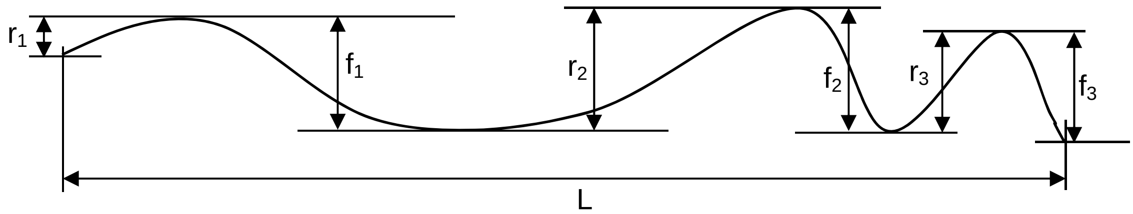
Figure 18: Effect of the gradient

$$F_{gradient} = -F_G \sin \beta$$

Vehicles travelling up a slope will encounter a force component of gravity opposed to their direction of travel and have to expend additional energy to keep their speed constant. In the case of a downward slope, the downhill gravity component acts to aid propulsion. However, as the downward speed has to be controlled, the energy gain from descending cannot be fully realised and some of the energy will be converted into heat by braking. This can be partially averted if recovery systems are in place to store the energy gain. In addition to this the gear setting and thus the working point of the engine will be different for driving uphill compared to driving downhill.

Associated parameter

Vertical alignment can be characterized by a longitudinal road gradient given as angle β in degrees or radians relative to the horizontal or as inclination in %. For longer road sections with varying gradients measures like Rise and Fall (RF) can be used. RF is defined as the sum of the absolute values of the height of all rises and falls of a road section divided by its length (Figure *19*).



$$\boldsymbol{RF} = \frac{\sum_i |\boldsymbol{r}_i| + \sum_j |\boldsymbol{f}_j|}{\boldsymbol{L}}$$

Figure 19: Definition of Rise and Fall (RF)

Options for NRA influence

Longitudinal gradients are typically determined in the planning and construction phase of a road and are fixed for a long time. Changes require additional substantial construction work. Environmental assessment in the planning phase could also include information on expected vehicle energy use as part of the overall and call for optimization of road trajectories. The MIRAVEC project will cooperate with the LICCER sister project on this topic.

2.4.2 Crossfall

Description of the mechanism

Pavements are designed with a transversal inclination called crossfall for traffic safety reasons, to make it possible to safely pass curves with different radius and for water drainage purposes. The crossfall is defined as the angle between the ideally flat inclined road surface and the horizontal.

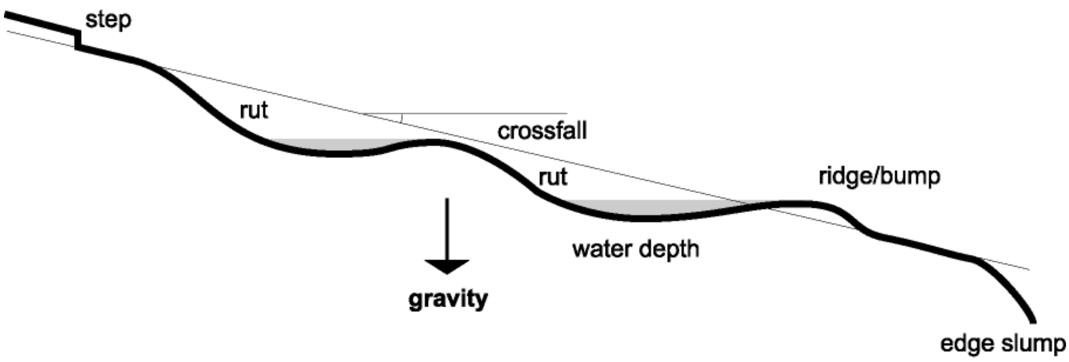


Figure 20: Crossfall and transversal unevenness features

The crossfall creates a gravity force component F_y towards the lower edge of the road which has to be counteracted to stay in the lane. This causes a driving resistance F_{side}, because the tyre will not be parallel to the direction of travel.

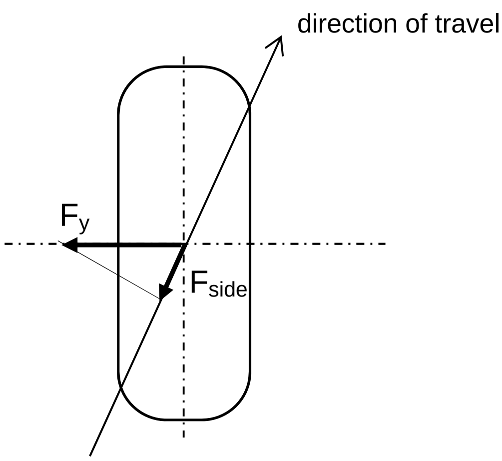


Figure 21: Action of sideways forces on the wheel and resulting driving resistance force F_{side}

Associated parameter

The crossfall is a road design parameter and is fixed at the time of road construction. It will be given as an angle of transversal inclination measured in degrees of arc.

Options for NRA influence

Crossfall is a design parameter of roads which is checked at the time of construction and can be closely controlled by NRAs. However, whilst resurfacing can result in some changes, it is usually not possible to make significant changes to it before a major rebuilding takes place. Transversal unevenness is monitored during the lifetime of pavements for safety reasons. For this reason, sufficient data should be available. The development of deep ruts can typically require maintenance actions like a repaving which would then also reduce the negative impact on fuel consumption.

2.4.3 Horizontal alignment (road curvature)

Description of the mechanism

Driving through curves in a road requires an additional centripetal force component in addition to the propulsion forces in the direction of travel to keep the road vehicle on the road trajectory. This force has to be provided by the tyre-road contact, which leads to increased tyre deformation and additional losses. This creates an additional contribution to the driving resistance F_{side} caused by sideways forces.

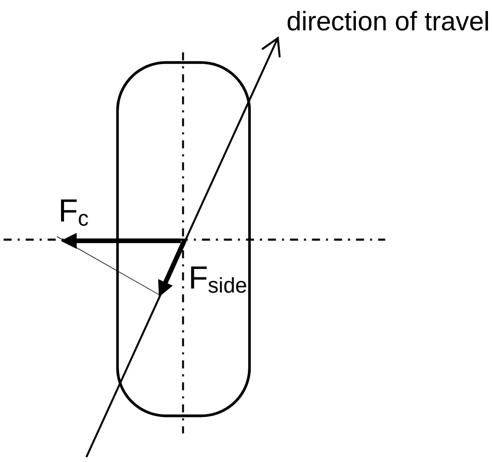


Figure 22: Action of centrifugal forces on the wheel and resulting driving resistance force F_{side}

The combined driving resistance F_{side} due to crossfall and centrifugal force is given in [4] as:

Side force resistance:

$$F_{side} = -\frac{F_y^2}{C_A}$$

where

$$F_y = m \cdot \left(\cos(\gamma) \cdot v^2 / R - 9.81 \cdot \sin(\gamma) \cdot \cos(\beta)\right)$$

F_y is the side force acting on the vehicle

C_A is the tyre stiffness [N/rad]

γ is the crossfall angle [rad]

β is the longitudinal slope [rad]

R is the radius of curvature [m]

Where the first term corresponds to the effect of road curvature and the second term contains the effect of the crossfall that occurs even without curvature (see also [20] and [21]).

An additional effect of horizontal curvature is the impact of curves on the driving speed. Curves with small radii of curvature will require a speed reduction before entering the curve.

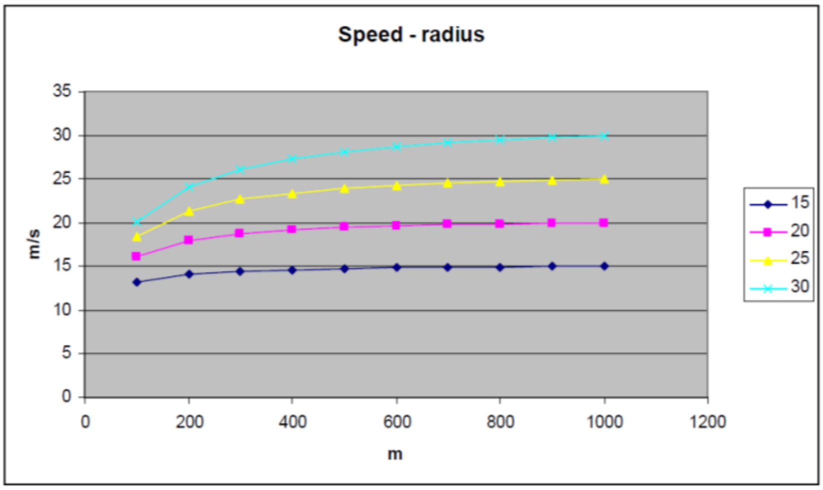


Figure 23: Curve speed as function of radius and of straight road desired speed (from [13])

Associated parameter

Roads can be characterized by the frequency of the occurrence of curves and their radius of curvature. Composite measures like the average degree of curvature (ADC) can be used to characterize longer road sections. The ADC is defined as the weighted average of the curvature of a curvy road, with the lengths of its curvy sections being used as weights. The horizontal curvature is defined as the angle subtended at the centre by an unit arc-length of the curve. The curvature is proportional to the inverse of the radius of curvature. The curvature of the curvy section is given as

$$C_i = \frac{180{,}000}{\pi R_i}$$

where

C_i curvature in degrees/km for the road section I with length L_i

R_i radius of curvature in m for the road section i

These can then be combined to the ADC of the total section with length L:

$$ADC = \frac{1}{L}\sum_i C_i\,L_i$$

Options for NRA influence

The occurrence of curves and the radius of curvature are determined in the planning phase of roads by the NRAs and cannot be changed without a major reconstruction. This effect therefore has to be considered in the planning stage. The MIRAVEC project will cooperate with the LICCER sister project on this topic.

2.4.4 Road width and lane and carriageway layout

Description of the mechanism

The width of roads and the lane and carriageway layout does not directly influence fuel consumption, but it can affect the traffic flow and vehicle speed. Insufficient overall road capacity in comparison with the traffic volume will lead to congestion and stop-and-go traffic. The effects of stop-and-go traffic are described in 2.5.2. Narrow lanes will also induce drivers to slow down due to the reduced lateral distance to passing vehicles and stationary objects, even if the traffic is free-flowing. If there is no separation from traffic in the opposite direction, further speed reduction due to road safety and insufficient sight distances may be necessary. The choice of speed and the presence of stop-and go-traffic will influence road vehicle fuel consumption.

The influence of varying road width on the free flow speed is modelled in [*13*] and an example can be seen in Figure 24.

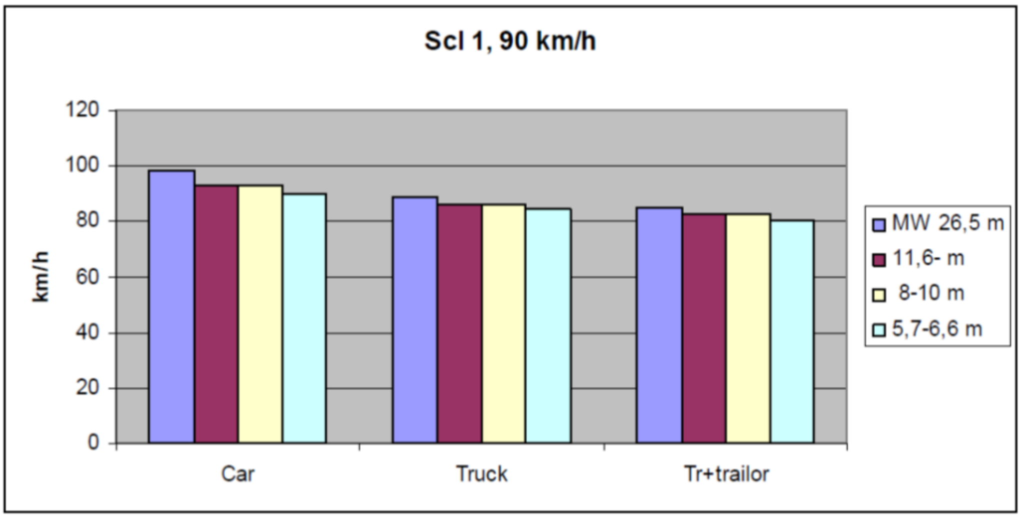


Figure 24: Free flow speed and road width at speed limit 90 km/h (EVA model, from [13])

Associated parameter

The road width and the number and layout of lanes and carriageways will be described by the appropriate geometric parameters e.g. road and lane widths, sight lines, or lane pattern.

Options for NRA influence

This feature of the road is determined in the planning and construction phases. Changes typically require additional construction or rebuilding operations.

2.4.5 Intersections and roundabouts

Description of the mechanism

Intersections and roundabouts mainly interact with the traffic flow by introducing additional accelerations, decelerations, and curves into the drive cycle (see section 2.5). These are typical features of lower-level road categories. Intersections are regulated by road signs and traffic lights, while roundabouts generally use only traffic signs. The occurrence of these features induces a reduction in average vehicle speed coupled with more changing of gears and braking losses. Fuel consumption will be higher compared to travelling at the same constant average speed.

Associated parameter

On a link level the number of intersections and roundabouts per km can be used as a modelling parameter. Intersections need to be classified into those only regulated by traffic signs and those with additional traffic lights.

Options for NRA influence

The presence of intersections and roundabouts is determined in the planning and construction phases by the NRAs. Changes typically require additional construction or rebuilding operations.

2.4.6 Tunnels

Description of the mechanism

The difference between tunnels and open-air road sections in terms of fuel consumption is limited to some specific effects. The presence of tunnels can entail speed limits or access restrictions for certain types of vehicles, which interacts with the traffic flow and composition (see 2.5). Driving in tunnels requires the use of vehicle lights, which increases the energy use of this type of auxiliaries during the daylight hours in countries without 24 hour lighting requirements. Air resistance in tunnels may be increased, especially if the tunnels act to channel winds into the tunnel entrances (although that might reduce air resistance in the opposite direction). Tunnels may reduce adverse meteorological effects such as rainfall, snow and general wind effects.

Associated parameter

The presence of a tunnel on a link level can be described by the number and length(s) of the tunnel(s). The individual possible effects described above will be modelled by using the appropriate individual parameters like wind speed.

Options for NRA influence

The presence of tunnels is determined in the planning and construction phases by the NRAs. Changes typically require substantial additional construction operations.

2.5 Group C: Traffic properties and effects of infrastructure interaction with the traffic

2.5.1 Traffic volume (AADT) and composition

Description of the mechanism

The overall traffic volume and its composition are basic properties of the traffic running on a specific road. Traffic volume determines the number of vehicles using a specific road or road section within a defined time period and is therefore a main determinant of the fuel consumption and greenhouse gas output attributable to this road section. Overall energy use of road vehicles on this link can be simply computed from sum of the individual fuel consumptions of the different vehicle categories. Traffic volume is typically linked to the road category, with higher-level roads carrying more traffic. The road traffic emission and fuel consumption tool HBEFA [27] distinguishes the following road categories for non-urban driving in descending order of expected traffic volume:

- Motorway
- Semi-motorway
- Trunk/Primary road
- Distributor/Secondary road
- Local/Collector road
- Access/residential road

The traffic composition, defined as the relative shares of the individual vehicles categories, also plays an important role, as the fuel consumption of different vehicles can differ considerably. The relative share of heavy goods vehicles (HGVs) is especially important due to their large impact on overall energy use. For the purposes of modelling traffic volume has to be subdivided into the individual traffic volumes of the vehicle categories. A distinction between passenger cars and HGVs is the minimum requirement, however, for improved accuracy more vehicle classes need to be used. HBEFA [27] distinguishes the following vehicle categories:

- Passenger car
- Light duty vehicle (< 3.5 t, including e.g. minibuses, trucks, camper vans)
- Heavy duty vehicles (> 3.5 t), subdivided into
    - Single truck
    - Truck with trailer
    - Articulated truck
- Coach (tour coach, holiday coach)
- Bus (urban bus, public transport bus)
- Motorcycle

Associated parameter

The overall traffic volume is typically described as annual average daily traffic (AADT), i.e. the total number of road vehicles using a specific road section during one year, divided by

365 days. This measure can also be adapted for shorter time intervals or to distinguish between weekday and weekend traffic. If no specific data are available, the average AADT for the road category can be used. The AADT of a specific vehicle category can be given as absolute figure or as share of the overall AADT.

$$AADT = \sum_i AADT_i$$

Options for NRA influence

The overall expected traffic volume and traffic composition is an important design parameter for roads. The required capacity of roads is mainly determined in the planning and construction phases. The actual traffic volume and composition in the operational phase can to some extent be controlled by traffic management via traffic lights, road markings, driver information and other ITS measures. Specific vehicle categories can be regulated by tolling and access control measures.

2.5.2 Traffic flow

Description of the mechanism

The traffic flow describes the average travel profile of the vehicle collective on a specific road section. Free-flowing traffic is the situation where it is possible to travel at a constant speed without being forced to accelerate or brake. The opposite situation is stop-and-go traffic, where frequent idling, acceleration and deceleration phases dominate over phases with constant speed. Stop-and-go traffic results in a low average speed and increased fuel consumption due to the idling, acceleration and deceleration phases. In [*27*] and [*28*] four “levels of service”, corresponding to combinations of speed and traffic capacity, are distinguished:

1. Free-flowing traffic (constant high speed)
2. Heavy traffic (constrained but constant speed)
3. Saturated traffic (heavy and unsteady traffic, , variable speed, possible stops)
4. Stop and go (congestion, low speed, frequent stops)

A schematic diagram of the four cases can be seen in Figure 25:

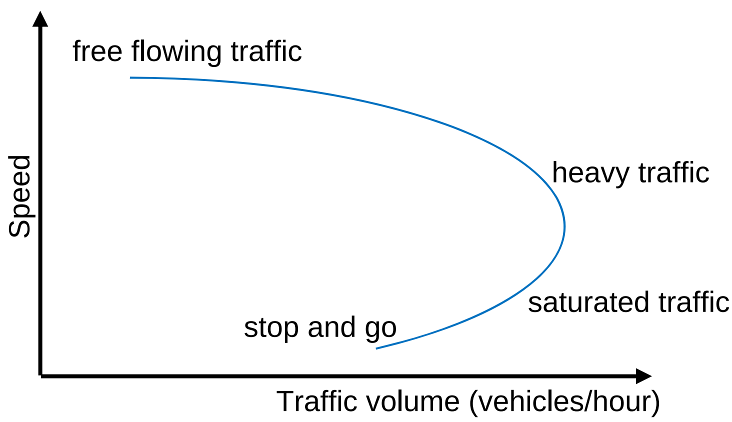


Figure 25: Different types of traffic flow situations

Associated parameter

The standard situation is typically assumed to be free traffic flow. The occurrence of stop-and-go traffic can be modelled with an increased share of idling, acceleration and deceleration phases in the drive cycle.

Options for NRA influence

NRAs try to avoid congestion and stop-and-go traffic by using sufficient traffic capacities in road design, and by management of the traffic flow in the operational phase. Traffic management will include the operation of traffic lights, information screens and variable road signs, providing travel information to drivers via radio and navigation systems and if necessary intervening directly by regulating access to parts of the road infrastructure.

2.5.3 Traffic speed and speed restriction measures

Description of the mechanism

The traffic speed distribution is an important influencing parameter for determining vehicle fuel consumption. It will determine the possible speed choices and gear selection for the individual vehicle. In general road vehicle fuel consumption will tend to rise with increasing vehicle speed. However, this can be substantially modified depending on the actual drive cycle characteristics with regard to e.g. acceleration, braking, presence of gradients, etc. The most frequent speed restriction measures are speed limits, which can be general or local, permanent or temporary, and are typically indicated by road signs. The actual vehicle speed can also be reduced by road features like deliberate narrowing at dangerous points, or introduction of obstacles like speed bumps, ridges or changes to very uneven road surface like paving stones. This is typically accompanied by warning signs indicating the reason for the measure.

Associated parameter

The speed distribution in a vehicle collective travelling on a road section can be described by a probability density function describing the share of vehicles at a specific speed. Simpler descriptors are the average speed v of the whole collective or of individual vehicle categories. Another possible descriptor is the speed not exceeded by 85% of vehicles (v_{85}). In free-flowing traffic the speed distribution has been found to approach a Gaussian shape, while speed limits will lead to a flattening or skewing [*29*].

Options for NRA influence

NRAs can influence the actual traffic speed in the short term only in the frame of traffic management mainly by controlling speed limits, traffic signs, road markings and driver information. Traffic speed is also an important factor in road planning and construction, in the form of a design speed for road sections and elements of the road layout intended to influence speed.

2.5.4 Traffic lights, road signs, road markings and ITS measures

Description of the mechanism

Road equipment like traffic lights, road signs and information screens are the main technical tools for traffic management. They will help to influence the traffic and individual drivers by conveying information about traffic situation, speed limits, potential obstacles, accidents or access restrictions. In contrast to the pavement and road layout they can be changed and influenced relatively quickly. Their impact on fuel consumption of the road vehicles is indirect by controlling other parameters like vehicle speed, traffic flow and composition, or traffic volume distribution on the network level.

Associated parameter

These installations need to be characterised in terms of their role in the framework of overall traffic management. Their effect will be described by their influence on other parameters e.g. vehicle speed.

Options for NRA influence

This road equipment is operated in the framework of traffic management by NRAs. Its presence enables NRAs to indirectly influence other variables with an impact on road vehicle fuel consumption.

2.5.5 Driver behaviour

Description of the mechanism

The behaviour of individual drivers can have a considerable influence on vehicle fuel consumption. Drivers e.g. choose the vehicle speed and gear setting, initiate acceleration and braking, or control the vehicle in curves, all of which can lead to higher or lower fuel consumption. Driver behaviour is influenced by a large number of factors, among them also the layout of and feedback from the road infrastructure as well as road signs and traffic management measures.

In order to model driver behaviour, it is categorized based on classes of driver types derived from investigations of large groups of persons. At this level of abstraction a driver behaviour model consists of a set of rules describing the typical reactions to different situations with the associated control inputs to the vehicle.

Based on the statistical evaluation of a large number of experiments, typical driving patterns can be derived for specific traffic situations, which can represent the average driver behaviour in the defined setting. In HBEFA (see [*27*] and [13]) a traffic situation (TS) leading to specific driving pattern is characterized by the following parameters:

- Area type (rural/urban)
- Road category
- Speed limit
- Traffic flow situation ("level of service", see 2.5.2)

Figure 26 shows an example for a driving pattern in HBEFA.

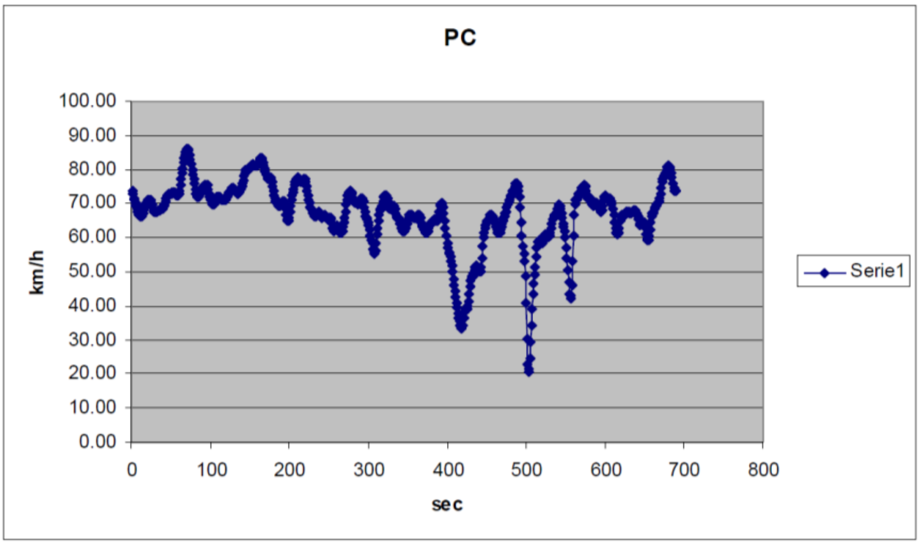


Figure 26: Example for a HBEFA driving pattern for the following traffic situation: rural area, distributor road, speed limit 70 km/h, free-flowing traffic (from [13])

Associated parameter

In modelling the relevant parameter is the choice of a driving pattern from a predefined set based on the traffic situation. This attempts to model the average driver influence of a large number of actual drivers with a similar behaviour. More advanced models may also include different driver types (e.g. careful, aggressive). However, for the purposes of modelling the road infrastructure influence using the average driving pattern is preferable.

Options for NRA influence

Driver behaviour can be influenced by road layout, road signs, traffic management, and in general all road features which generate feedback to the driver. This can include issues such as the influence of noise on the speed selection of drivers. However, generally NRA control pertains only to external influences on driver behaviour. For the purpose of simplified models using the abstraction of average driving patterns as described above, it is sufficient to control the road category, traffic speed and traffic flow.

2.6 Group D: Vehicle and tyre properties including potential effects of current trends in vehicle and tyre development

2.6.1 Vehicle type

Description of the mechanism

The vehicle type determines many aspects of the basic energy distribution within the vehicle as shown in Figure 1. Engine and transmission losses and the range and energy requirements of auxiliaries are determined by the vehicle type and specific model. Engine fuel efficiency and the amount of power that can be transferred to the drive axle for propulsion limit the possible effects any parameter from groups A and B of this report can have. The torque and power that can be delivered by the engine and the fuel consumption connected to it can be described by engine maps (Figure 27). In connection with information on the gear settings and characteristics of the transmission this can be used to determine the power transferred to the drive axle.

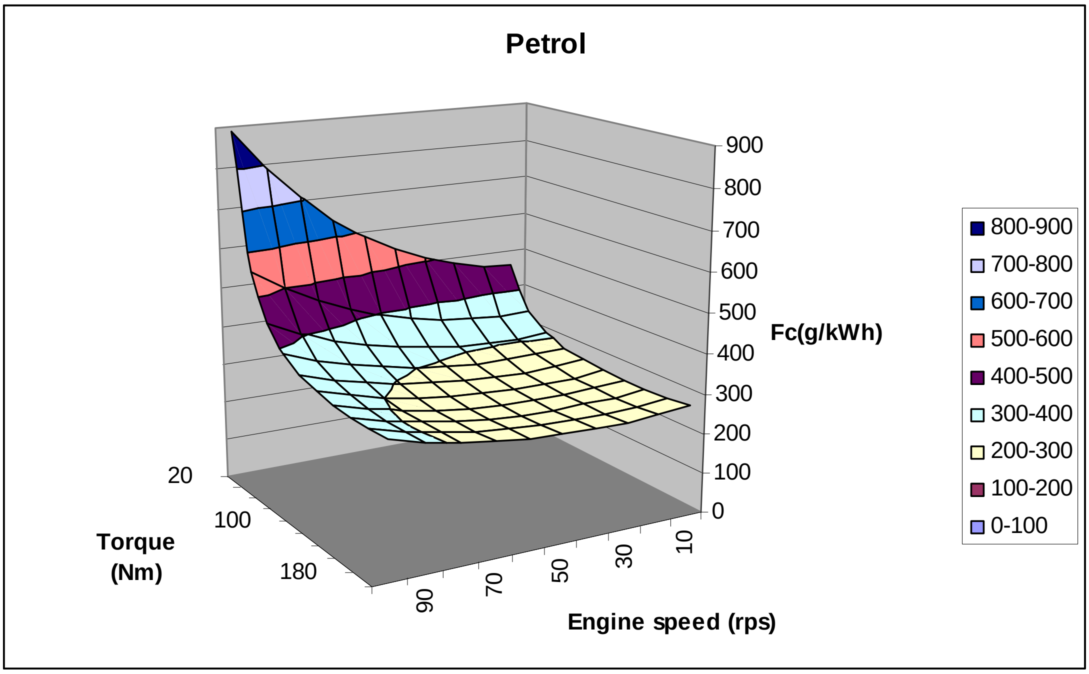


Figure 27: Engine map (g/kWh) for a petrol engine. Engine specification: petrol; year model 1996-2003; PMrat=100 kW; displacement=1.95 dm^3 (from [30]).

Fuel consumption is also dependent on the overall mass, which determines the inertial forces needed to be overcome when accelerating and decelerating. These inertial forces can be described by

$$F_{inert} = (m + m_{rot})\frac{dv}{dt}$$

where m is the vehicle mass and m_{rot} the effective inertial mass of the rotating parts of the vehicle like wheels and transmission (see [4]). The distribution of masses, steering mechanisms and tyre suspensions determine the vehicle dynamics and its possible reactions to road infrastructure. Vehicle mass and loading is especially relevant for heavy duty vehicles. The frequency of acceleration an deceleration events where the inertial forces are relevant are determined by the traffic flow (see 2.5.2) and driving pattern (see 2.5.5).

The frame design determines the air resistance coefficient for the whole vehicle (see section 2.6.3). Moreover, the vehicle type usually also limits the range of possible tyres which can be used with the vehicle.

Substantial changes of the internal energy distribution are expected with the introduction of more hybrid and fully electric vehicles (EVs). The main differences to vehicles with internal combustion engines (ICE) are the high efficiency of electric engines, the use of batteries as power storage and the elimination of greenhouse gas emission by the vehicle itself. With fully electric vehicles the greenhouse gas emission happens at the power plant producing the electric energy used to charge the battery of the electric vehicle. For this reason it is necessary to perform a well-to-wheel analysis to compare EVs and ICE vehicles. The analysis in [*31*] gives maximum ICE efficiencies of up to 45% compared to efficiencies of electric engines between 60% and 95%. The well-to-wheel efficiency for conventional ICE passenger cars is between 16% and 23%. For electric vehicles the efficiency from battery to wheel is between 72% and 77%. In Europe the power plant efficiency is typically 45% and the power grid efficiency 93%, resulting in a well-to-wheel efficiency of electric vehicles of 24% to 26%. While this is higher than for ICE vehicles, a substantial decrease in greenhouse gas emission requires the use of renewable energies and low-emission power plants in combination with the electrification of vehicles.

The main consequences of the introduction of hybrid and fully electric vehicles will be the growing importance of other energy loss mechanisms due to the substantially increased efficiency of the engine. This means that all infrastructure effects contributing to rolling resistance as well as the other driving resistances caused by gradient, curvature or crossfall can be expected to gain importance. This is even more important as the current battery technology limits the achievable range before recharging, which can become a decisive factor in the adoption of EV technology.

The possible use of platooned vehicles (i.e. a group of electronically connect vehicles traveling close together) may provide appreciable fuel savings in the future.

Associated parameter

Due to the large number of parameters determined by the vehicle type, the vehicle properties need to be generalized if a specific subset of influencing factors like those linked with the road infrastructure shall be studied. Therefore average vehicles representing large vehicle categories are used in models. A typical choice is the subdivision of vehicles into passenger cars, trucks and trucks with trailers or the use of the HBEFA [*27*] vehicle categories:

- Passenger car
- Light duty vehicle (< 3.5 t)
- Heavy duty vehicles (> 3.5 t)
- Coach (tour coach, holiday coach)
- Bus (urban bus, public transport bus)
- Motorcycle

Options for NRA influence

NRAs have a rather low influence on the specifics of vehicle technology. A certain influence is the existence of some basic access restrictions like legal requirements for the minimum design speed of vehicles to access motorways. Weigh-in-motion systems can be used to enforce access restrictions linked to vehicle mass, which could help to reduce fuel consumption. Some urban authorities have implemented access restrictions based on their emissions categories and trials have been undertaken with different forms of priority lane usage.

2.6.2 Tyre type and condition

Description of the mechanism

The mechanical properties of the tyre determine the tyre reaction to road surface and the associated rolling resistance losses. The tyre deformation is due to the tyre load and the applied forces in longitudinal and lateral direction. The stress-strain curve shows a hysteresis, which means that this is not a fully elastic process and that energy is dissipated as heat.

$$E \propto \int \varepsilon\, \sigma\, tan(\delta)\, dV$$

where

E	dissipated energy
ε	strain amplitude
σ	stress amplitude
$tan(\delta)$	loss factor of the rubber
dV	volume element

The typical contributions of the different tyre components to the overall tyre rolling resistance can be given as follows [*32*]:

1) Tread: 50%
2) Bead: 10-15%
3) Sidewall. 5-10%
4) Liner: 1%
5) Ply: 5-10%
6) Belt: 20%

Tyre rolling resistance is significantly affected by the tyre temperature. Tyre warm-up and tyre temperature need to be closely controlled in rolling resistance testing of tyres. Further influencing factors are tyre inflation and tyre load as well as the tread depth, toe-in and camber angles. In addition to the effects on rolling resistance, tyre mass determines the inertial forces and the tyre dimensions affect the air resistance of the individual tyre.

The rolling resistance of tyres is determined as a tyre-specific property by testing on a steel drum according to ISO 28580 [*8*]. Rolling resistance testing and labelling of new tyres according to ISO 28580 is now mandatory in the EU. The EU regulation 661/2009 [*33*] has fixed upper limits for the tyre rolling resistance C_R determined according to ISO 28580 of between 0,008 and 0,012 depending on the tyre category. EU regulation 1222/2009 [*34*] has introduced a labelling system with classes from A to G, where tyres in the highest energy efficiency class A are required not to exceed a rolling resistance C_R determined according to ISO 28580 of 0,0065. These regulations will affect the type approval and labelling of new tyres, which means the effects of worn and retreaded tyres are not taken into account. Due to the test method, rolling resistance values for tyres cannot fully describe their performance on real road surfaces. The flat steel surface represents an extreme case not found in real road pavements.

Associated parameter

Like the vehicle type, the tyre type is a parameter combining a complex set of parameters. When focusing on road infrastructure parameters in modelling, it is necessary to define a small number of reference tyres which are deemed to sufficiently represent the most important classes of tyres.

Options for NRA influence

NRA influence on tyre technology development itself is very low. Some influence is possible through the permitted tyre sizes (e.g. the use of super-singles tyres), the use of winter tyres and required tread depth. Other authorities can play a role in enforcing appropriate tyre usage.

2.6.3 Air resistance

Description of the mechanism

Road vehicles experience air resistance as the flow resistance of travelling through air. Air resistance increases quadratically with the speed relative to the air [20][4]. Besides the relative speed of the vehicle in the air also the exposed surface area and the aerodynamic shape of the vehicle play an important role. The moving vehicle compresses the air in front of it and creates a zone of reduced pressure behind itself, leading to a pressure gradient opposed to the vehicle movement. In addition to this friction between the vehicle surface and the adjacent layers of air as well as the generation of eddies dissipates energy contribute to air resistance.

Associated parameter

The air resistance force is defined as follows:

$$F_{air} = \frac{1}{2}\rho_{air} A C_L v^2$$

Where

F_{air}	air resistance
ρ_{air}	air density
A	area of the expose cross-section
C_L	air drag coefficient
v	speed of the vehicle relative to the air

The effects of vehicle shape, eddy formation and boundary layer behaviour are accounted for in the air drag coefficient C_L, which modifies the basic flow resistance formula resulting from Bernoulli's law. Typical C_L values for passenger cars in 2010 are given as 0.30 - 0.33 in [22]. The most important variable is the airspeed, the speed of the vehicle relative to the surrounding air, which is different from its travelling speed when wind is present. Due to the quadratic influence air resistance rises considerably with airspeed which is determined by driving speed and the prevailing wind speed and direction. Both have to be taken into account to determine the relevant vector component of the airspeed to be used in the determination of air resistance. Lateral air speed components, which are perpendicular to the direction of travel, have to be taken into account as additional side forces and will also influence the vehicle buoyancy in air. The contribution of air resistance to overall fuel consumption rises from approximately 4% in urban driving conditions to approximately 11% for driving at highway speeds (see [1]). The speed where air resistance equals rolling resistance is given as approximately 70-80 km/h for average passenger cars in [23]. [22] indicates that a 10% reduction in air resistance leads to a reduction of 3 to 4% in fuel consumption for an average passenger car in a driving cycle with 33% motorway driving.

Options for NRA influence

Improvements in vehicle technology have reduced the $C_{L,}$ values of passenger cars from around 0.9 in 1900 to about 0.3 in 2010 (see [22]). NRA influence on aerodynamic vehicle technology itself is low; however, there are some options for designing infrastructure to avoid high air resistance due to wind. Prevailing wind directions should be taken into account when designing narrow or exposed sections of the road and its surroundings like tunnels and bridges. Existing natural features like mountains, hills and forests as well as road equipment structures like noise barriers or enclosures provide protection from wind. Information from fluid dynamics simulations can be used in order to avoid detrimental eddy formation at the edges of artificial structures and predict the effect from such installations.

Reduction of air resistance for vehicle collectives can also be achieved by forming platoons of vehicles (e.g. trucks) with very short time gaps to take advantage of the slipstream generated by the leading vehicle. Fuel savings are reported to be approximately 4 to 7% for 2 trucks in [24] and up to approximately 20% for 3 trucks in [25]. To ensure safe operation platoons currently mainly rely on automated vehicle control and vehicle-to-vehicle communication. Vehicle platooning on motorways was investigated in the SARTRE EU project [26]. Widespread use of platooning would also mean that it should be taken into account in road infrastructure design and road traffic control, possibly complementing the vehicle-to-vehicle communication with vehicle-to-infrastructure communication.

2.7 Group E: Meteorological effects

2.7.1 Temperature

Description of the mechanism

Ambient temperature plays an important role in determining road and tyre temperatures, which in turn influences the rolling resistance mechanism. However it has to be noted that temperatures of rolling tyres will typically increase above ambient temperature due to the heat generation by deformation. Therefore rolling resistance testing requires that tyres have reached their equilibrium temperature before starting the test [8]. Ambient temperature will also influence cold start and evaporation emissions of ICE vehicles, which lead to increased fuel consumption [27]. Additionally, larger ambient temperature variations will also increase the use of auxiliaries like air conditioning, which in turn increases the overall energy demand.

Associated parameter

The parameter most widely used in modelling and measurements is ambient air temperature T, given in °C, which in turn influences the road surface and tyre temperatures and acts as a basic parameter for other temperature-related effects in the vehicle. The temperature correction of ISO 28580 [8] gives an indication of the temperature dependence of the rolling resistance:

$$C_{R,25} = C_{R,T}\left(1 + k(T - T_0)\right)$$

Where

$C_{R,25}$	Corrected rolling resistance at 25 °C
C_T	Rolling resistance at temperature T
k	Constant, given as
	0.008 for passenger car tyres,
	0.010 for truck and bus tyres with Load Index $\leq$ 121
	0.006 for truck and bus tyres with Load Index $>$ 121
T	Ambient temperature
T_0	Reference temperature T_0 = 25 °C

The value of k indicates that an increase in ambient temperature of 1 °C approximately corresponds to a decrease in rolling resistance of 1%.

Options for NRA influence

There are few options for direct NRA influence. Pavement temperature can be influenced to some extent by choosing a road surface type. Pavements with brighter surface colours indicating a higher albedo, e.g. concrete surfaces, can be used to achieve lower pavement surface temperatures, which in turn influence rolling resistance. The potential quantitative influence of this effect needs to be investigated.

2.7.2 Wind

Description of the mechanism

Depending on speed and direction wind can lead to a substantial increase in air resistance (see 2.6.3) by raising the relative speed of the vehicle with the moving air. If the wind direction is different from the travelling direction of the vehicle, a lateral component of air resistance will also contribute to the driving resistance created by side forces (see 2.4.3.) This can occur on exposed areas such as bridges. Tunnels and narrow valleys will also contribute to channelling winds into the traveling direction of the roads.

Associated parameter

Wind can be characterised based on wind speed v_{wind} and direction with regard to the vehicle and its travelling direction. For example, a frequently occurring frontal wind speed like v_{wind} = 10 km/h will add 10% to the relative aerodynamic speed of a vehicle travelling at 100 km/h. The compound influence of vehicle and wind speed on air resistance is described in 2.6.3. (see also [20] and [23]).

Options for NRA influence

The prevailing wind speeds and directions in a certain area cannot be changed, but need to be taken into account in road design. The layout of roads and especially tunnels and bridges needs to take prevailing wind conditions into account to prevent excessive increases and changes in air resistance. Screening by natural obstacles like mountains, hills, valleys and forests and artificial structures like noise barriers, tunnels and other enclosures can prevent vehicles from being exposed to high wind speeds. However, care must be taken not to introduce additional unfavourable air flows and eddies, especially at the edges of such structures. Information on possible fuel savings due to the reduction of air resistance can be found in section 2.6.3.

2.7.3 Water

Description of the mechanism

The presence of water on the road surface will in general lead to a higher rolling resistance, but is also a primary safety concern. The tyre needs to displace the water to remain in contact with the road surface, which manifests as a force hindering propulsion. At a sufficient speed, the tyre may completely lose surface contact and aquaplaning occurs, with severe safety implications. At lower speeds slip-stick effects with a more complex influence on rolling resistance will occur (see [20][21] and Figure 28).

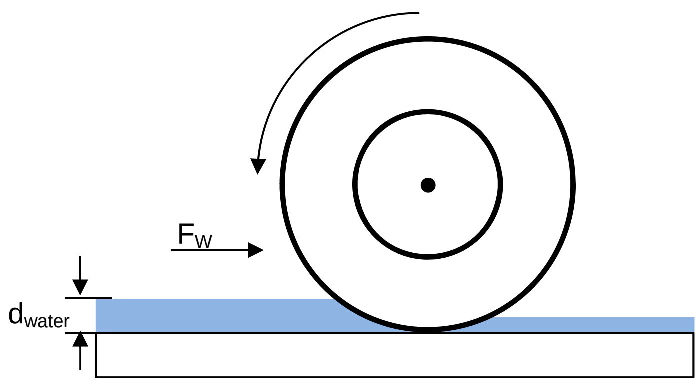


Figure 28: Driving resistance due to water on the pavement

Associated parameter

The presence of water on the road surface can be described by the water film thickness d_{water}.

Options for NRA influence

The short-term water input from rainfall cannot be controlled by NRAs. However, information on the long-term meteorological conditions as well as on the frequency and water volume of rainfall events will form the basis for the design of the drainage systems, the road layout in terms of crossfall and the surface drainage capability in the form of a sufficient macrotexture and/or porosity. Therefore the overall water removal capacity is partially determined at the planning and construction phase of the road but can still be modified during its working life through maintenance and adaptation of the pavement and the drainage system.

2.7.4 Snow and ice

Description of the mechanism

The presence of snow and ice on the road surface in itself presents a safety issue with considerable consequences, like reducing safe driving speeds. The loss of friction will require the use of winter tyres, studded tyres or snow chains, which can be expected to also increase the rolling resistance. In addition to the effect described for water in 2.7.3, the effects of snow can be compared to having a considerably more flexible pavement, which leads to increased losses. An indication is shown in [35]; however, the exact details are the subject of on-going research.

Associated parameter

The presence of snow or ice on pavements can be described by the thickness of the snow or ice layer d_{snow} or d_{ice}.

Options for NRA influence

NRAs seek to avoid this unsafe situation by performing winter maintenance and removing snow and ice as much as possible.

3 Conclusions from the analysis

The objective of the analysis presented in this report was to identify the contributing effects and influencing factors for the energy consumption of road vehicles, with a special focus on the effects of road infrastructure.

Table 1 shows an overview of the analysed effects and properties as well as the most important parameters for each effect and the expected level of influence NRAs can exert over it.

Table 1: Overview of analysed effects and properties

No.	Name of effect or property	Group	NRA influence level (H,M,L)	Parameters
1	Rolling resistance (pavement)	A	H	C_R
2	Texture	A	H	MPD, texture spectrum
3	Longitudinal unevenness	A	H	IRI
4	Transversal unevenness	A	H	Rut depth
5	Surface defects	A	H	Defect area density
6	Road strength	A	H	deflection, C_R contribution
7	Vertical alignment (Gradient)	B	H	Angle β or %, RF
8	Crossfall	B	H	Angle γ
9	Horizontal alignment (Curvature)	B	H	R_{Curv}, ADC
10	Road width and lane and carriageway layout	B	H	w_{Road}
11	Intersections and roundabouts	B	H	Level of service
12	Tunnels	B	H	Level of service, $v_{average}$, v_{85}
13	Traffic volume and composition	C	L	AADT, %
14	Traffic flow	C	M	Level of service
15	Traffic speed and speed restriction measures	C	M	$v_{average}$, v_{85}
16	Traffic lights, road signs, road markings and ITS measures	C	M	Level of service, $v_{average}$, v_{85}
17	Driver behaviour	C	M	driving pattern
18	Vehicle type	D	L	vehicle type
19	Tyre type	D	L	tyre type
20	Air resistance	D	M	F_{air}
21	Temperature	E	L	T
22	Wind	E	L	v_{Wind}, α_{Wind}
23	Water	E	M	d_{water}
24	Snow and ice	E	L	d_{snow}, d_{ice}

The following conclusions were drawn from the analysis:

- The five chosen groups of effects and properties showed clear differences in the level of possible NRA influence. Groups A and B comprise effects where there is a clear impact of infrastructure and which are governed by parameters typically under the control of NRAs. Group A contains effects which could be monitored and influenced by pavement-related measures during the working life of the road. The effects in Group B should be considered in the planning and construction stages of the road, ideally with a tool like the one to be developed by the sister project LICCER. Groups C to E in general contain effects with lower chances or more indirect ways for NRA influence like e.g. ITS measures. Therefore the grouping should provide a good working basis for WP2.
- The parameters used for describing the different effects in modelling show variety in terms of their descriptive value and data availability:
  - Some parameters like MPD, IRI, RF, ADC, or v_{Wind} can already be used directly in models. Some of these may in the future be superseded by more advanced parameters which are more suitable for the development of models, like e.g. the enveloped MPD for texture or the weighted longitudinal profile for unevenness.
  - Other parameters, notably the ones describing traffic flow and driver behaviour need to be classified into e.g. typical driving cycles as they are too complex to be described by single numbers.
  - The parameters connected with the details vehicle and tyre type are very numerous. For an analysis focused on road infrastructure effects, they need to be combined into very simplified composite parameters. This is effectively equivalent to choosing an average vehicle and average tyres for each vehicle category to be able to focus on the infrastructure-related effects.
  - There are parameters whose effects are difficult to isolate. The prime examples are vehicle speed which is influenced by many other phenomena, and temperature, which can substantially modify other effects.
  - The data availability for pavement and road properties which are part of regular monitoring by NRAs is already quite high. This is the case for longitudinal and transversal unevenness, texture, road strength, surface defects, data for traffic volume and composition, and meteorological data. Road design parameters from group B like gradients or crossfall are available to NRAs from the planning and construction phases. Data on the specifics of vehicle and tyre type as well as details of driver behaviour are more difficult to obtain.
- Knowledge gaps exist for several effects:
  - Modelling of the pavement contribution to rolling resistance is mainly based on texture and unevenness. It is currently unclear if the contribution of surface defects is sufficiently captured by these other parameters. There is an on-going discussion about the magnitude of the effect of road and the advantages of choosing rigid over flexible pavements for fuel consumption.
  - The effects of gradients, crossfall and curvature can be described in technical terms as forces acting on the vehicle. The effects of road width and layout, intersections, roundabouts and tunnels are more indirect and act on the driving speed and driving behaviour in general. These effects are small and more difficult to quantify.
  - The effect of ITS measures on the traffic flow and vehicle energy consumption needs to be determined individually for each measure. While this analysis has

been performed for several measures, this and the classification of driver behaviour are on-going research topics.

- The developments in vehicle and tyre technology will have a major impact on vehicle fuel consumption. The response of the market to the new fuel efficiency requirements for tyres still remains an open question. For vehicles the degree of market penetration of electric vehicles cannot be predicted accurately.
- There are still considerable knowledge gaps about the actual importance of the presence of precipitation like water, snow and ice on the pavement.

4 Conclusions and recommendations for WP2

The key recommendations for further analysis in WP2 of this project can be summarized as follows:

- The review of existing models as to which parameters are already included and in which way they are integrated into the model should consider all effects and parameters analysed in WP1. It is to be expected that only a subset of the parameters will already be included in the models.
- The proposals for the addition of new parameters currently not included in the models can be based on the parameters from WP1, taking quality of the available quantitative description and data availability into account.
- Quantitative analysis may not be possible or not sufficiently accurate at this time. However, even a rough description (e.g. by introducing classes) could help to take new effects into account.
- WP1 has focused on providing a complete view of all possible influencing factors. If analysis in WP2 shows some of them to be of negligible importance, they can be omitted from further stages of the analysis. This has already been indicated for some effects where pertinent information was available.
- For the evaluation of uncertainties in the predictions of existing models, it is proposed to use the subset of effects and parameters shown in Table 2.

Table 2: Proposed subset of effects and parameters for uncertainty modelling in WP2

No.	**Name of effect or property**	**Group**	**NRA influence level (H,M,L)**	**Parameters**
2	Texture	A	H	MPD, texture spectrum
3	Longitudinal unevenness	A	H	IRI
4	Transversal unevenness	A	H	Rut depth
7	Vertical alignment (Gradient)	B	H	Angle β or %, RF
8	Crossfall	B	H	Angle γ
9	Horizontal alignment	B	H	R_{Curv}, ADC
10	Road width and lane layout	B	H	w_{Road}
13	Traffic volume and composition	C	L	AADT, %
15	Traffic speed and speed restriction measures	C	M	$v_{average}$, v_{85}

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