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Influence of Rolling Resistance on CO_2

Authors: Iddo Riemersma, Peter Mock
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1. Introduction

The 9th meeting of the Informal Subgroup on the Development of the WLTP Test Procedure (WLTP-DTP) (16–18 April 2012, Bern) included a discussion of whether, and how, the selection of tires should be implemented in the test procedure. One of the proposals was to link tire selection to the combined vehicle test weight proposal, the current version of which is described in document WLTP-DTP-10-02. The idea was to select, from the range of tires on offer for the vehicle model, a tire in the worst rolling resistance class for the vehicle with the highest test mass, and a tire in the best rolling resistance class for the vehicle with the lowest test mass. This led to some discussion on the influence that rolling resistance could have on the slope of the CO_2 versus mass interpolation line. ICCT offered to provide input on the influence of rolling resistance on CO_2 in order to make a well-informed decision on this issue. In the WLTP-DTP Subgroup on Lab Process–Internal Combustion Engines (LabProcICE) meeting on 22 May 2012 in Brussels, it was agreed to leave tire selection out of the combined vehicle test weight proposal. Still, there were some concerns (mainly by the Japan Automobile Manufacturers Association) about the width of the tire labeling classes in terms of CO_2, which led to their proposal that the worst-case tire from the worst rolling resistance class should be tested. The intent of this paper is to quantify the expected effect of tire classification on CO_2 as input for the discussion on tire selection.

2. General considerations

Before the issue is addressed, some fundamentals should be reviewed.

The forward motion of a vehicle is opposed by the following resistances:

- Air drag of the bodywork, which is dependent on aerodynamic performance (c_w value) and frontal area, and increases with the square of the vehicle speed
- Rolling resistance, which is (almost) independent of vehicle speed and is proportional to vehicle weight[1]
- Transmission losses due to friction of bearings and gears, which are (almost) independent from engine and vehicle speed
- Vehicle inertia, which is proportional to vehicle weight but is only present during acceleration of the vehicle (during deceleration, this is a driving force)

Road inclination also plays a role, but that is outside the scope of this report because no vertical road profile is included in the World-harmonized Light-Duty Vehicle Test Cycle (WLTC).

The total sum of the resistance forces—referred to as the road load—will be balanced by the driving force at the wheels of the vehicle. This driving force is produced by the vehicle engine through the transmission to the wheels. Fuel needed for this engine performance is converted to CO_2 in the combustion process with an efficiency that depends on engine load and speed, among other factors.

The above information enables us to draw two important conclusions:

- The relative share of rolling resistance in the total road load depends not only on vehicle parameters (mainly aerodynamic performance and weight), but also on driving cycle parameters (vehicle speed profile).
- A change in rolling resistance cannot be straightforwardly translated into a corresponding effect on CO_2, because engine efficiency is also affected by a change in road load.

At first glance, these conclusions seem to complicate the matter considerably. However, according to an SAE paper by Michelin, an almost linear relation can be found

1 A small effect on rolling resistance related to vehicle speed can be expected above 80 kmh (TNO, 2006). We neglect this influence.

Authors: Iddo Riemersma is principal at Sidekick Project Support. Peter Mock is managing director of the ICCT's European office. Address correspondence concerning this paper to peter@theicct.org.

About this series: At the United Nations level, a new test cycle and test procedure for light-duty vehicles is currently being developed. ICCT is part of the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) working group, and is providing technical input to the project. Papers in this series summarize selected contributions from ICCT to the WLTP working group, and make the information available to a broader audience.

between CO_2 and rolling resistance, with only the vehicle mass as a parameter (Barrand & Bokar, 2008). This surprising conclusion is the result of the following:

- The effect of rolling resistance on CO_2 is linear. When comparing two tires with different rolling resistance coefficients on the same vehicle over the same driving cycle, the *absolute* difference in road load will be proportional to the difference in rolling resistance coefficients. Although the driving cycle can change the contribution shares of the different road load components, the difference in the amount of fuel consumed will be independent of the cycle.
- For typical engine operation points, fuel consumption maps show that a decrease in engine load translates into an almost linear decrease in fuel flow rate. So even though a change in road load is affecting the engine efficiency, the resulting effect on fuel consumption is nearly linear. Because engine efficiency decreases at lower engine loads, the linear correlation coefficient between road load and fuel consumption will be less than 1.

In other words, it can be concluded that even though the fuel consumption over a driving cycle is dependent on parameters related to speed and dynamics of the cycle, the difference in the amount of fuel consumed between two tires on the same vehicle and over the same test cycle will be proportional to their rolling resistance coefficients and independent from that cycle.

In Barrand and Bokar (2008), this is represented by an empirical relation with the following formula:

$$\Delta FC = \alpha \cdot \Delta C_{RR} \cdot M$$

where ΔFC is the change in fuel consumption (which may also be expressed as ΔCO_2), α is the linear correlation coefficient (which takes into account engine efficiency among other parameters), ΔC_{RR} is change in rolling resistance, and M is vehicle mass.

3. Literature sources

A number of literature sources were found that address the influence of rolling resistance (henceforth RR) on CO_2 emissions. However, none of them are very specific in terms of driving conditions (type approval test cycle or real-life) or vehicle/tire parameters (vehicle mass, baseline RR coefficient, etc.). They are mostly referred to as a general rule of thumb, normally presented as a percentage of fuel consumption reduction related a percentage of lower RR. Note that Barrand and Bokar (2008) concluded that for vehicles with identical mass, the effect of RR on CO_2 is better represented as an absolute difference rather than a relative figure. Still, these sources at least give some indication of the effect that is searched for.

An overview of literature sources with information on the effect of low-RR tires (LRRTs) is presented in TNO (2006). The text and table below are copied from this report:

[Excerpt, TNO Science and Industry (2006)]

A short review of relevant literature has revealed the range of the CO_2 reduction potential of energy efficient tyres but also some other interesting issues as well. Table 5.1 summarises the reduction potential retrieved from various bibliographic sources. The first remark that can be made on these data is that there is an evident inconsistency on what is considered low friction tyre. This was expected due to the lack of specific definition of low rolling resistance tyres (LRRT). Two major approaches are distinguished; reduction potential expressed with regard to a certain rolling resistance decrease (usually 10%) or expressed in relation to the generalised idea of a low rolling resistance tyre. It is estimated that the second equals approximately a 20% reduction of the resistance factor. Additionally, a clear difference is observed between older estimates [IEA 1993] and newer ones. This difference reveals the aforementioned technological improvements that were achieved during the last decade. Finally it must be commented that there is no referenced methodology on which these estimates were based. Due to the lack of a predefined protocol, most of them are based either on measurements that were conducted under different conditions or on calculations that adopted different assumptions. Therefore the presented numbers cannot be directly compared.

Table 5.1. Review of the CO_2 reduction potential through the use of energy efficient tyres.

Source:	**LAT**	**IEEP 2004**	**CARB 2004a**	**NRDC 2004**		**Penant 2005**	**IEA 1993**	
Rolling resistance factor decrease	10%	LRRT	10%	20%	LRRT	LRRT	10%	10%
CO_2 emissions benefit	1.7%	2%	2%	3–4%	2–6%	3–4%	1.0%	0.5–1%
Notes	Real-world estimates			Based on measurements	Best case		IEA estimates	Manufacturer estimates

A U.K. Department for Transport report (DfT, 2008) mentions a study by TRL (Watts et al., 2006), which concludes that a 10% reduction in RR will result on average in a 3% reduction in fuel consumption. Relative to the other sources, this 3% seems to be a rather strong effect. However, for the calculations in DfT (2008), an effect between 1 and 2% is used for a variation of 10% in RR, which is more in line with the other sources. Further investigation into the substantiation of the claimed 3% effect found that TRL estimated 30% of the road load over the New European Driving Cycle (NEDC) to be attributable to RR. Depending on vehicle characteristics, this share of RR may be lower. Furthermore, they assumed that a 10% lower RR, leading to 3% lower road load, would translate into 3% lower fuel consumption. The effect of reduced engine efficiency due to lower engine load was apparently not considered.

An expert from the tire manufacturer Continental said that his company estimates that a RR difference of 10% would correspond to a 1.6% change in fuel consumption (Continental, n.d.).

According to the U.S. Environmental Protection Agency (U.S. EPA and NHTSA, 2011), referring to a study by Ricardo Inc., an improvement of 10% in RR would reduce CO_2 emissions by 1.9%.

Finally, Barrand and Bokar (2008) validated their findings by measurements and found that a reduction for the RR coefficient of 1 kg/tonne (roughly 10%) translates into a 1.7% CO_2 reduction for a gasoline-fueled vehicle and a 1.4% CO_2 reduction for a diesel-fueled vehicle. Actually, only absolute differences are given in their paper (as mentioned, they found that absolute differences are more accurate than relative differences), but for comparison reasons they are presented here as a percentage.

There is quite good agreement among these sources, so in general we conclude that on average a 10% lower RR will result in 1.5 to 2% lower CO_2 emissions.

4. Simulations with Ricardo Response Surface Modeling (RSM) tool

Apart from the literature survey, ICCT also performed simulations with a tool that was developed by Ricardo. The Ricardo Data Visualization Tool enables parameter variation analyses for different light-duty vehicle configurations, engines, and transmissions in the 2020–2025 time frame (EPA, 2011). By choosing specific vehicle configurations and varying only RR, the effect on CO_2 could be accurately determined. Because the simulation runs included a range of vehicle weights, the effect of weight is also shown. The following two configurations were chosen as input because they were expected to be more or less representative of the 2020 vehicle fleet:

- B-class light-duty vehicle (e.g., Toyota Yaris), stoichiometric direct-injection engine with turbocharger and 6-gear dry dual-clutch transmission
- D-class light-duty vehicle (e.g., Ford Mondeo), stoichiometric direct-injection engine with turbocharger and 8-gear dry dual-clutch transmission

Parameter variation for the simulation was chosen as follows:

- Rolling resistance: the borders of RR classes as defined in EU Tyre Labelling Regulation 1222/2009 (European Community, 2009b) (see Table 1)
- Weight: 800 to 1400 kg for the B-class vehicle; 1200 to 1800 kg for the D-class vehicle (chosen arbitrarily to show the effect of weight on the CO_2 difference between RR classes)

During the development of the RR classification scheme, it was decided that the borders between classes would be separated from each other by 15% increments; as a consequence, RR class B is narrower than RR class F. According to EU Regulation 661/2009, tires in RR class G are currently not allowed on passenger cars, and as of 1 November 2017, tires in RR class F are prohibited for new type approvals of passenger cars (and 1 year later for all passenger cars) (European Community, 2009a).

Table 1. Rolling resistance classes as defined in EU Tyre Labelling Regulation 1222/2009.

Class	Rolling resistance (kg/tonne)
A	<6.5
B	6.6 to 7.7
C	7.8 to 9.0
D	Not used
E	9.1 to 10.5
F	10.6 to 12.0
G	>12.1

Graphical results of the simulation runs for the NEDC cycle are presented in Figures 1 and 2. The lines represent the border values of the RR classes; the areas in between show the range of CO_2 values for tires in each RR class. Apart from the NEDC, simulation results were also obtained for the U.S. Federal Test Procedure (FTP) cycle. Absolute differences in CO_2 between RR classes at the lowest and highest vehicle weights are presented in Tables 2 and 3.

Table 2. Absolute NEDC and FTP CO_2 differences between RR classes for B-class vehicle (FTP results in parentheses).

B-class vehicle weight	Lowest CO_2 difference (g/km)	Highest CO_2 difference (g/km)
Low (800 kg)	1.7 (1.8)	2.9 (2.8)
High (1400 kg)	2.8 (3.1)	3.4 (4.3)

Table 3. Absolute NEDC and FTP CO_2 differences between RR classes for D-class vehicle (FTP results in parentheses).

D-class vehicle weight	Lowest CO_2 difference (g/km)	Highest CO_2 difference (g/km)
Low (1200 kg)	2.9 (2.7)	3.7 (3.9)
High (1800 kg)	3.6 (3.2)	5.1 (3.3)

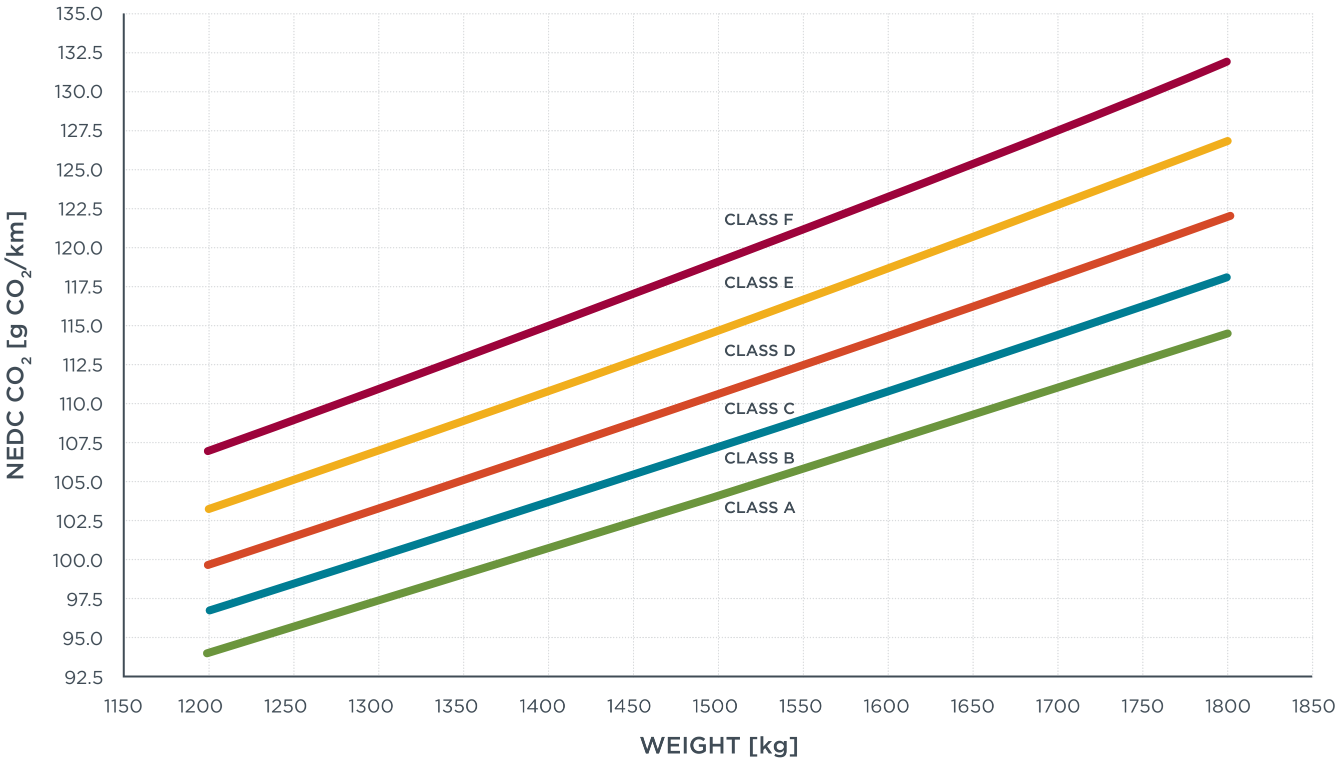

Figure 1. NEDC CO_2 simulation results for B-class vehicle as a function of vehicle weight for six RR classes.

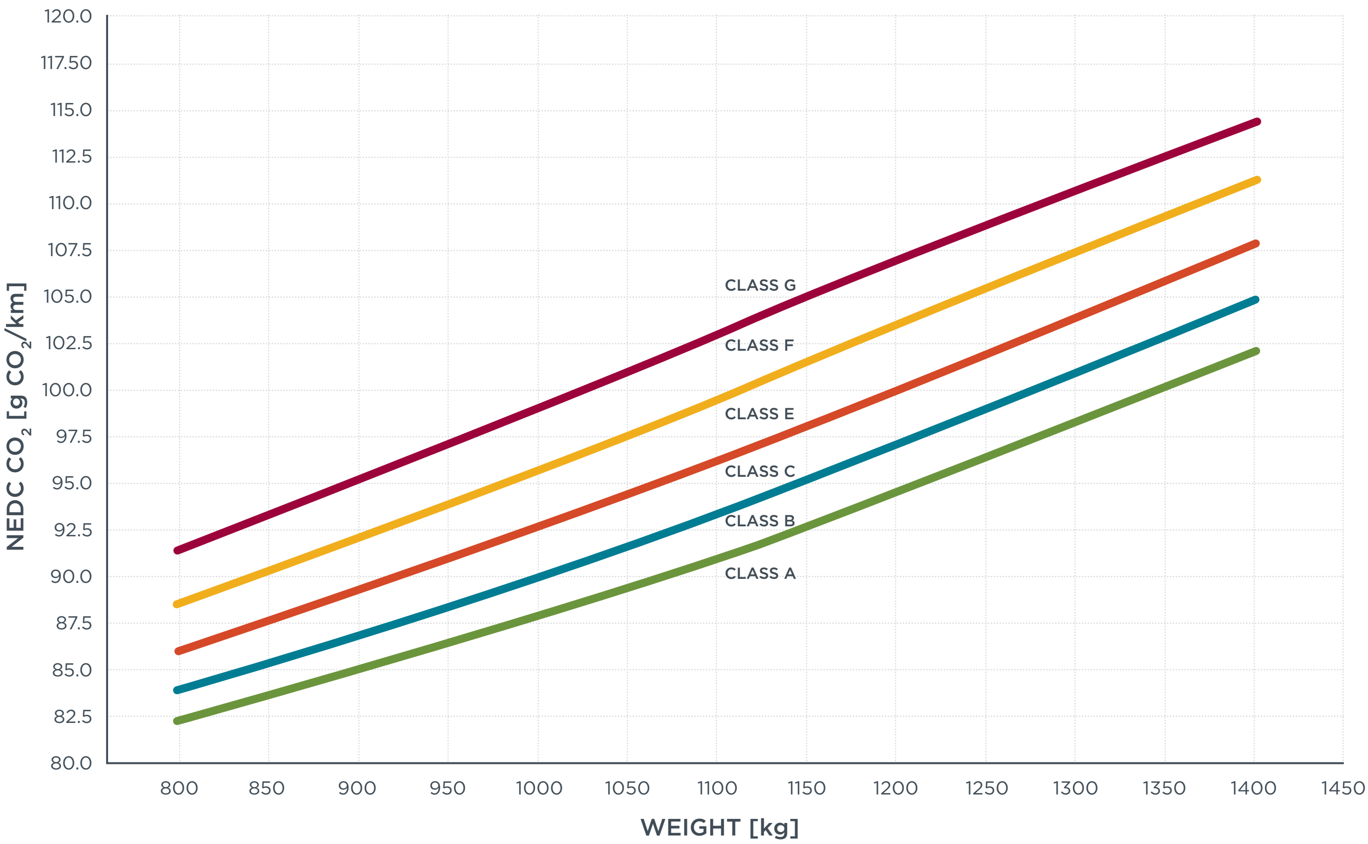

Figure 2. NEDC CO_2 simulation results for D-class vehicle as a function of vehicle weight for six RR classes.

The figures and tables lead to a number of observations:

- The CO_2 differences between RR classes increase with the weight of the vehicle. This is explained by the empirical formula introduced by Barrand and Bokar (2008), which suggests that the effect of RR on CO_2 increases linearly with weight.
- The CO_2 difference tends to be larger for the higher RR classes. Because the widths of the RR classes are not constant but increasing toward higher RR classes, this finding seems explicable. Scientifically it would be more correct to express the CO_2 differences per unit of kg/tonne RR, but this was not done because our objective is to quantify the effect of RR classes on CO_2.
- Although the simulation results of NEDC and FTP cycles do not give full correspondence on CO_2 differences between RR classes, the trends and order of magnitude are quite similar. This coincides with the conclusion that for vehicles with identical mass, the results would be independent of the test cycle used (see section 2 above).

The average absolute effect on CO_2 for an average-weight B-class vehicle is around 2.9 g/km per RR class. For an average-weight D-class vehicle this is around 3.5 g/km per RR class. The higher value for the D-class vehicle is related to its higher weight. Dividing these numbers by the average weight of the vehicle classes (in tonnes) brings them closer together, to 2.6 and 2.4 g/km of CO_2 per tonne of vehicle weight, respectively.

The analysis of these simulation results is so far only based on an absolute difference in CO_2. As suggested in section 2, the absolute difference is considered to behave in a more constant fashion than the relative difference. However, we also calculated the relative differences in order to compare these simulation results with the literature sources in section 3 (Table 4). Both the difference per RR class and the difference per 10% change in RR are shown. Because the RR classes are separated by 15% change in RR, the relative difference per 10% change in RR is calculated simply by multiplying by a factor of 10/15.

Table 4. Average relative CO_2 difference between RR classes for NEDC and FTP cycles (relative difference per 10% change in RR shown in parentheses).

Test cycle	Average CO_2 difference, B-class vehicle (%)	Average CO_2 difference, D-class vehicle (%)
NEDC	3.4 (2.2)	2.8 (1.8)
FTP	2.8 (1.9)	3.0 (2.0)

Summarizing the average CO_2 differences of Table 4, this will be close to 3% per RR class and 2% relative difference per 10% change in RR. The effect on CO_2 shown by this last figure can be directly compared to the references found in the literature, and seems to be in accordance with those values (see section 3), especially when it is considered that recent studies show higher percentages than older ones. This can be explained from the fact that NEDC and FTP CO_2 values tend to decrease as a result of the realized improvements in fuel efficiency. Because the effect of RR on CO_2 is absolute, the resulting effect in relative terms will understandably be higher.

5. Width of tire labeling classes

Although not directly within the scope of this report, some considerations need to be mentioned with respect to the origin and width of the RR classes.

The RR coefficient of a tire is not a value that can easily be determined, mainly for two reasons:

- The coefficient is not constant but depends on parameters such as temperature, tire pressure, and tread depth.
- It is a relatively low force in response to a high load on the tire (around 100 N per 1000 kg of load), so any friction in the testing equipment will lead to inaccuracies.

The first issue can be overcome by setting strict testing requirements that enable repeatable test results. The second one, however, leads to changes in coefficients between two testing machines, even on the same tire under the same circumstances. This is mainly due to small differences in internal friction. To overcome such inaccuracies, an alignment procedure has been developed, laid down in the ISO 28580 procedure. This allows the labs to align their testing equipment against a “virtual lab” that averages the results of seven reference labs. Without such alignment, there was reasonable concern that inaccuracies between labs (or even between identical testing machines) could result in differences of more than one RR class of the proposed labeling categorization (UNECE, 2009). Representatives of the European Tyre and Rim Technical Organisation concluded that a 1.5 kg/tonne width should be defined for the labeling scheme, which translates into roughly 15% (European Commission, 2008).

This explains that there is a clear need to have a labeling scheme for tire RR (Pike, 2011), not only for customer information but also to cope with variation and inaccuracies. To accommodate this purpose, the width of these classes was not arbitrarily chosen but was carefully considered to have sufficient “contrast” between tire RR classes.

6. Conclusions

- There is quite good agreement among (recent) literature sources. In general, they suggest that a 10% lower RR will result in 1.5 to 2% lower CO_2 emissions.
- Simulation results for typical future vehicle configurations (around 2020) support this conclusion, with an average of 2% CO_2 difference per 10% variation in RR coefficient.
- When the effect on CO_2 is expressed as an absolute value, the difference between two tires over the same test cycle will be proportional to their RR coefficients and independent from that cycle. Therefore, the CO_2 difference is better expressed as an absolute value rather than a percentage.
- The effect of RR variation on CO_2 increases linearly with vehicle weight.
- Because of the nature of the tire RR labeling scheme, absolute differences in CO_2 emissions are larger for the higher RR classes.
- Absolute differences in CO_2 emissions between RR classes range from 1.7 g/km for a low-weight B-class vehicle on lowest-RR tires to 5.1 g/km for a heavy-weight D-class vehicle on highest-RR tires. On average, the CO_2 difference per RR class was found to be 2.5 g/km per tonne of vehicle weight.
- The RR classification scheme was not developed only for the purpose of tire labeling; it is also needed to overcome variation and inaccuracies in the RR coefficient test procedure. The width of the RR classes is chosen as the minimum needed, given the expected inaccuracies among testing facilities.
- As a result of using the tire RR labeling scheme for tire selection, the difference in measured CO_2 emissions between two tires in the same RR class will on average be less than 2.5 g/km per tonne of vehicle weight. As of 1 November 2017, tires in the F class will no longer be allowed in Europe, which is expected to slightly reduce this value (considering that this is the class with the largest width).
- It seems justifiable to select tires according to their RR class and not their RR coefficient, because there are some difficulties in accurately determining an actual value for RR. On the other hand, it can be assumed that the measurement inaccuracy will not exceed the width of any of the tire RR classes. Selecting the tire according to its RR value will therefore undoubtedly lead to smaller tire-related differences in CO_2. The tire manufacturer’s declared RR value (on the basis of which the tire is classified) could then serve as a basis for selecting the worst-case tire.

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