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DRIVING RESISTANCES OF LIGHT-DUTY VEHICLES IN EUROPE: PRESENT SITUATION, TRENDS, AND SCENARIOS FOR 2025

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EXECUTIVE SUMMARY

Corporate CO_2 and fuel economy standards require strong efforts by the automotive industry in several regions of the world to improve efficiency and reduce vehicles loads. Traditional vehicle concepts have to be reworked. The driving resistances of a light-duty vehicle (LDV) directly affect fuel consumption and CO_2 emissions. Reducing the main parameters of mass, aerodynamic drag, and rolling resistance improve fuel efficiencies and reduce the total CO_2 emissions. Cutting driving resistances can contribute considerably to reaching the common and the manufacturers' specific emission targets and to mitigating climate change effects.

Available studies on driving resistances and their impacts mainly focus on the mass parameter. Rolling resistance is strongly controlled by tire suppliers and aerodynamic drag by vehicle manufacturers, and data normally are not published. This study comprehensively investigates all vehicle based parameters influencing LDV driving resistances. Existing databases on European LDV mass, aerodynamic drag, and tires were evaluated to quantify the current status and trends of LDV fleet and segment averages. Technical scenarios for 2025 were derived, and achievable reductions in terms of CO_2 emissions were assessed. Furthermore, trends for the U.S. market were derived from official road load databases published by the US EPA.

Mass

The 10-year EU trend is an annual weight increase of 0.4%. This trend occurs consistently for all car segments except for sport utility vehicles (SUVs), where the EU market has shifted on average to smaller and lighter versions. However, for most segments the mass curve has flattened over the past 3–4 years. In addition, the U.S. sales-weighted mass data show a roughly 0.4% annual weight decrease over the past 10 years, after adjustments to the EU vehicle classification to account for U.S. vehicles being larger. Substantial reductions have been achieved for many recently released new model generations by applying lightweight materials and introducing material-saving production processes.

Rolling resistance

The situation of tire rolling resistance differs from other load parameters, as the technology required for drastic improvements is already on the market. Improvements are mainly a matter of cost and are under the control of both the vehicle manufacturers choosing original equipment tires and the vehicle owners determining the demand for after-market tires. While 10-year trend data are not available in Europe, trend data from the U.S. show a 1.3% annual reduction in rolling resistance.[1] The European situation until 2025 will be determined mainly by three regulatory measures:

- the prohibition of tires with high rolling resistance coefficient (RRC);
- the introduction of the EU tire labeling system; and
- the introduction of the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) as the regular type-approval procedure for LDV.

1 Rolling resistance trend is based upon individual model data, which are not sales-weighted. Sales-weighted mass data in the U.S. suggests that the individual model data are likely underestimating the annual reductions.

A 75% market share for tires of efficiency classes A and B (maximum rolling resistance coefficient of 7.7 kg/t) is expected in 2025, which corresponds to an annual average reduction of the rolling resistance of 2.1%.

Aerodynamic drag

The databases show rather small changes in total aerodynamic drag over the past 10 years for the most relevant vehicle segments. Only the J segment (SUV) features clear improvements, but this is mainly because of the intensified demand for smaller SUVs, which still have worse aerodynamic drag than smaller cars and increase the average for the total passenger car fleet. Improvements in aerodynamics (coefficient of drag) for the European market segments A to D are observable on the order of 0.5% per year, but are almost fully offset by increased frontal areas. Improvements in aerodynamics are often in conflict with other vehicle development targets, making aerodynamic improvements technically more demanding. The U.S. data, when adjusted to EU vehicle classification, show an annual decrease of 1.3% in total aerodynamic drag over the last 10 years.

Total CO_2 reduction potential

Potential load reduction scenarios for 2025 were based upon historical trends, best-in-class analyses, and assessments of future technology potential. Regarding technical feasibility, the total CO_2 reduction potential in 2025 was quantified between 14% (Scenario 1) and 25% (Scenario 2). Both scenarios assume that engines will be downsized and tailored to the specific performance requirements of each vehicle version. All three types of driving resistance parameters can contribute by rather similar amounts, although mass reduction gives the highest potential benefit of the three resistance parameters. The CO_2 sensitivity of rolling resistance is comparatively low, but low rolling resistance tires clearly exceeding the current market averages are already available. They are ready and easy to introduce, but need to be promoted by regulatory measures. Aerodynamic drag improvements are also promising, especially if the ongoing trend of enlarged frontal areas can be stopped, and the improvements in further streamlining the vehicle body can be fully transformed into CO_2 savings.

Table ES-1. CO_2 reduction potential due to improved driving resistances for the EU LDV fleet average, based on the WLTC driving cycle*

	Current trend (per year)	Scenarios		CO_2 % / 10% red.	CO_2 reduction 2025	
		1	2		1	2
Mass	**+0.4%**	-10%	-20%	-7%	-7%	-14%
Rolling Resistance	**-1.3%**	-25%	-35%	-1.5%	-4%	-5%
Aerodynamic Drag	**-0.3%**	-10%	-20%	-3%	-3%	-6%
Total CO_2 saving potential					**-14%**	**-25%**

** including assumed secondary mass effects and adjusted engine performance*

ABBREVIATIONS

a	Vehicle acceleration
A, B, C	Road load coefficients (U.S. labeling)
A_f	Frontal area
Acc	Acceleration
AD	Aerodynamic Drag (= C_d * A_f), with m^2 as the unit
C_d	Aerodynamic drag coefficient
CoC	Certificate of Conformity
CO_2	Carbon dioxide
DVT	Data Visualization Tool
EEA	European Environmental Agency
EPA	United States Environmental Protection Agency
ETRTO	European Tyre and Rim Technical Organisation
EU	European Union
F	Force
FC	Fuel Consumption
f_{RR}	Rolling resistance coefficient
f0, f1, f2	Road load coefficients (European labeling)
g	Gravity constant
I_{RP}	Inertia of rotating parts (expressed as mass equivalent)
KBA	Kraftfahrtbundesamt (Germany)
LDV	Light-duty vehicle
mass iro	Mass in running order (EU definition)
m_V	Vehicle mass
MY	Model Year
N1	Light Commercial Vehicles with a maximum mass not exceeding 3.5 tonnes
NEDC	New European Driving Cycle
PHEM	Passenger Car and Heavy Duty Emission Model
RG	Road Gradient
RR	Rolling Resistance
RRC	Rolling Resistance Coefficient
SAE	Society of Automotive Engineers
SUV	Sport Utility Vehicle

TMH	Test Mass High (WLTP)
TML	Test Mass Low (WLTP)
TU	Technical University
v	Vehicle velocity
VCA	Vehicle Certification Agency (United Kingdom)
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
α	Road gradient
ρ_{Air}	Air density

1. INTRODUCTION

The driving resistances of a light-duty vehicle (LDV) affect its total energy consumption. The reduction of the main responsible parameters mass, aerodynamic drag and rolling resistance directly reduces fuel consumption and CO_2 emissions.[2] With the introduction of CO_2 standards in many regions around the world, manufacturers are required to find ways to reduce the average emission level of their new vehicle fleet. Traditional vehicle concepts have to be reworked. Cutting driving resistances can contribute considerably to reach future CO_2 emission targets and to mitigate climate change effects.

Publicly available studies on the potential for reducing driving resistances often focus on vehicle mass reduction and in particular on the shares, benefits, and potentials of one particular lightweighting material. Suppliers of competing raw materials including steel, aluminum, different kinds of plastics, and other metals are performing studies on lightweight automotive construction (Steel: WorldAutoSteel, 2011; Ducker Worldwide, 2011. Aluminum: EAA, 2013; EAA, 2015; Ducker Worldwide, 2012. Plastics: PlasticsEurope AISBL, 2013; McKinsey & Company, 2012). Such published reports illustrate weight reduction potential from the specific supplier's perspective. In comparison, the objective of this study is to assess mass reduction potentials following an integrated approach by "best-in-class" analyses. The lightest vehicle model of each vehicle segment was identified representing the optimal combination of different lightweight materials currently achievable and setting the standard for future market averages. Furthermore, it should be noted that vehicle mass is the selected parameter in the EU to align manufacturers' specific CO_2 emission targets and is therefore under extensive surveillance of the European Commission (Kollamthodi et al., 2015).

Public studies on rolling resistances are mostly restricted to specific parameters (Peckelsen & Gauterin, 2013) or to selected high-performance tires (Vennebörger, Strübel, Wies, & Wiese, 2013). Publications including complete market overviews or even temporal developments of mean rolling resistance coefficients are missing. The situation on aerodynamic drag data is similar. Rare public studies focus on specific technical issues like benefits for electric vehicles (Wiedemann, Wiesebrock, & Heidorn, 2012) or on numerical simulation approaches (Schütz, 2011). Information on rolling resistance and aerodynamic drag are often under the direction of the tire and vehicle manufacturers. Their reluctance regarding the publication of resistance data is understandable as innovative technical improvements increase their competitiveness. Hence, little data on technical details and on reduction potentials are publicly available. In this study, available data sources on rolling and aerodynamic driving resistances are summarized, and new methods were applied to identify actual data of market products and to shed light on the 10-year trend development of these parameters.

In this report the future potentials of all relevant vehicle driving resistances are assessed comprehensively. Relating to the European market, this study illuminates the current status and trends for the LDV fleet and segment averages of the relevant driving resistance parameters. Common comprehensive databases are evaluated, and scenarios for future developments for 2020 and 2025 are provided, also assessing their technical potential and feasibilities. Trends for the U.S. market are also derived from official road load databases published by the US Environmental Protection Agency (EPA, 2014).

2 As fuel consumption and CO_2 emissions can be directly converted to each other, relative trends are similar for both. In the following only the term "CO_2 emissions" is used, always implicitly suggesting that the findings described in this report are also valid for fuel consumption to the same extent.

1.1 PHYSICAL PRINCIPLES OF THE DRIVING RESISTANCES

The actual CO_2 emissions of a vehicle depend on the vehicle's driving resistances, the powertrain's efficiency and the energy demand of potentially activated auxiliary consumers. The efficiency of the powertrain describes those parts of the total fuel's energy content that can be used for the mechanical propulsion of the vehicle.
The majority of the employed chemical energy gets lost by heat dissipation and friction in the powertrain. Engine efficiencies vary between different types of engines and also between different loads within the engine maps, described by engine speed and engine power (or torque). Accurate engine efficiency maps are essential for the application of numerical models to simulate vehicles' CO_2 emissions.

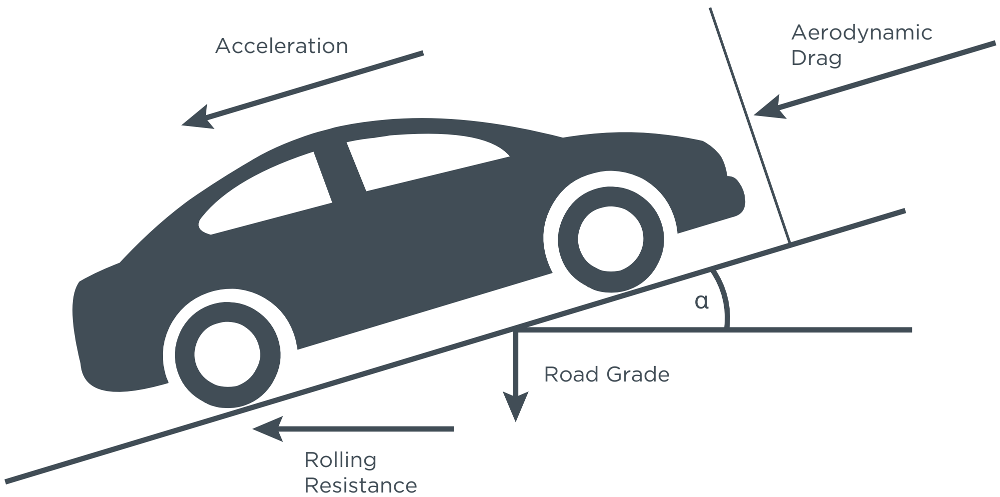

Figure 1. Resistance forces affecting a moving vehicle.

The driving resistances of a vehicle follow basic physical principles. The total forces occurring at the contact area between tires and road surface consist of four parts: aerodynamic drag, rolling resistance, acceleration and slope (Figure 1). These forces can be calculated by the following formulae:

Total force:

$$F_{Total} = F_{AD} + F_{RR} + F_{Acc} + F_{RG}$$

The *Aerodynamic drag* (F_{AD}) of a vehicle is determined by the aerodynamic shape of the body, described by the drag coefficient (C_d), and by the projected frontal area of the vehicle (A_f). The aerodynamic force increases with the square of the vehicle's velocity (v).

$$F_{AD} = C_d * A_f * \rho_{Air} / 2 * v^2$$

The *rolling resistance* forces (F_{RR}) are mainly determined by the tires, but also by parts of the driveline. They are characterized by the rolling resistance coefficient, f_{RR}, which is dependent on the vehicle's velocity. The mass of the vehicle (m_V) also has a linear influence perpendicular to the road.

$$F_{RR} = m_V * g * f_{RR} * \cos(\alpha)$$

The *acceleration* forces (F_{Acc}) increase proportionally with the vehicle's mass. Also the inertias of the rotating parts (I_{RP}), in particular tires, must be considered.

$$F_{Acc} = (m_V + I_{RP}) * a$$

The *slope* forces (F_{RG}) can be directly specified by the road gradient and the vehicle mass.

$$F_{RG} = m_V * g * \sin(\alpha)$$

With:

C_d	Aerodynamic drag coefficient
A_f	Frontal area
ρ_{Air}	Air density
v	Vehicle velocity
m_v	Vehicle mass
g	Gravity constant
f_{RR}	Rolling resistance coefficient
α	Road gradient
I_{RP}	Inertia of rotating parts (expressed as mass equivalent)
a	Vehicle acceleration

LDV fuel consumption and CO_2 emissions normally are measured on a chassis dynamometer under defined driving patterns and constant external conditions. The resistances at the roll(s) of a chassis dynamometer have to be adjusted to the vehicle's driving resistances in the real world and its mass. For this adjustment, measured rolling resistance and aerodynamic drag are used. The acceleration forces are adjusted by applying the matching inertia. Road gradients normally are not simulated on chassis dynos, but can be included by adjusting the inertia.

For the experimental determination of rolling resistance and aerodynamic drag a coastdown run with the test vehicle normally is performed beforehand. The vehicle is accelerated on a flat and straight road to a certain velocity (e.g., 130 km/h). Then engine and gearbox are decoupled from the drivetrain, and the vehicle coasts down until standstill. The velocities and times during this coastdown run are monitored continuously. A typical velocity-time course is depicted in Figure 2.

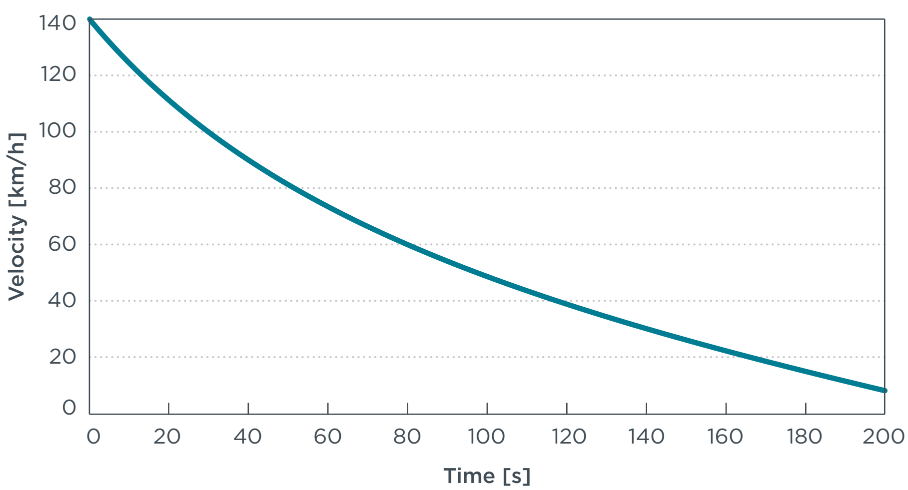

Figure 2. Typical course of vehicle's velocity during coast down (gearbox in neutral).

The force balance during the deceleration of the coastdown is described by the following formulae:

- $F_{Acc} = F_{RR} + F_{AD}$

- $(m_V + I_{RP}) * a = m_V * g * f_{RR} + C_d * A_f * \rho_{Air} / 2 * v^2$

Because of the speed dependency of the rolling resistance coefficient (f_{RR}), it is difficult to derive the relevant resistance coefficients (f_{RR} and $C_d * A_f$) directly from the experimental data. Instead, a quadratic correlation following the principle of the least squares deviation is applied. European regulations prescribe the use of six fixed-velocity intervals for this correlation (see next chapter). The basic formula for this approach is:

$F_{RR} + F_{AD} = f0 + f1 * v + f2 * v^2$

The derived factors are called the "road load coefficients." In the U.S. these are labeled as A, B, and C coefficients. In practice, these three factors are used together with the vehicle test mass to calibrate the dynamometer roll resistances. Finally, the vehicle at the chassis dynamometer test bench has to overcome the same forces as on the road during normal driving. This is controlled by additional dynamometer coastdown runs where the times needed for the predefined velocity intervals have to be identical to the coastdown behavior on the road. Some tolerances are permitted in the EU, but not in the U.S.

Figure 3 shows a typical distribution of rolling resistance and aerodynamic drag over a vehicle's velocity. Aerodynamic drag goes up with the square of the velocity, whereas rolling resistance is rather constant at low velocities, but increases strongly at high speeds. The figure is only schematic, as the real distribution of the forces and their absolute values strongly depends on vehicle and tire characteristics.

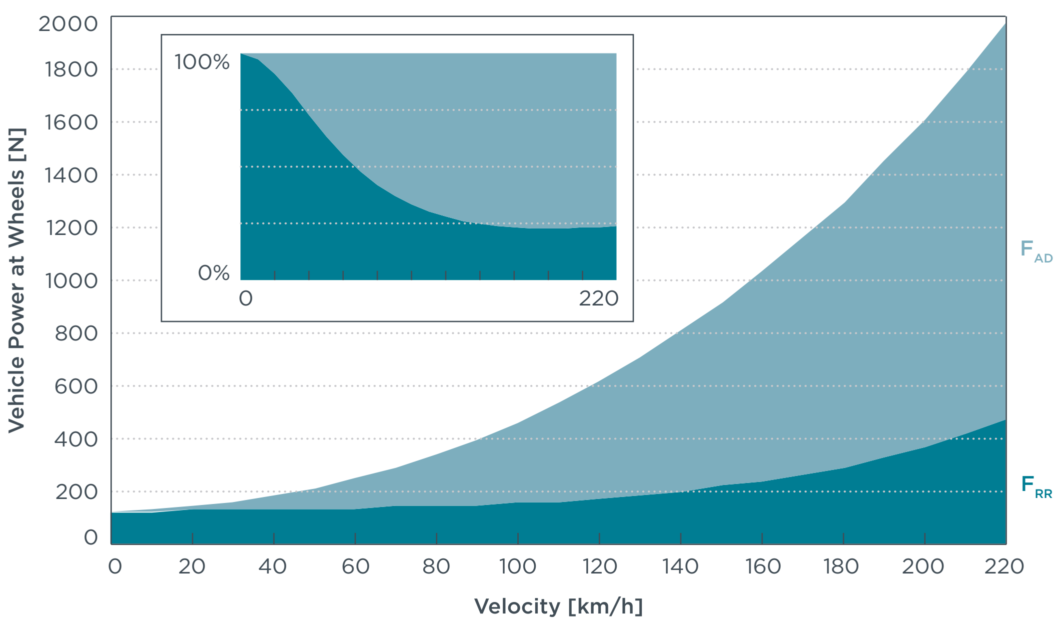

Figure 3. Typical distribution of rolling resistance force (F_{RR}) and aerodynamic drag force (F_{AD}) over vehicle velocity.

1.2 COASTDOWN RUNS – DIFFERENCES BETWEEN EU AND THE U.S.

The provisions on coastdown procedures deviate between Europe and the U.S. European regulations and are detailed and precisely describe the calculation procedure. Six fixed-velocity intervals are defined as described in Table 1. The U.S. approach on the determination of vehicles' road loads is different, as the agencies interpret vehicle road loads as physical parameters. It is the manufacturer's responsibility to determine vehicle road loads as close to reality as possible. The methodology applied is not prescribed. However, EPA uses defined Society of Automotive Engineers (SAE) standards to conduct confirmatory coastdown tests, thus manufacturers should calibrate any alternative procedure to these standards. The suggested specifications on covered velocity ranges are summarized in Table 1 and Figure 4.

Table 1. EU and U.S. velocity ranges for LDV coast down

Europe				U.S.		
Step	from (km/h)	to (km/h)	mean (km/h)	SAE J1263		
1	125	115	120	must include	80	km/h
2	105	95	100	min range	100–40	km/h
3	85	75	80	max speed	113	km/h
4	65	55	60			
5	45	35	40	SAE J2263		
6	25	15	20	Range	115–15	km/h

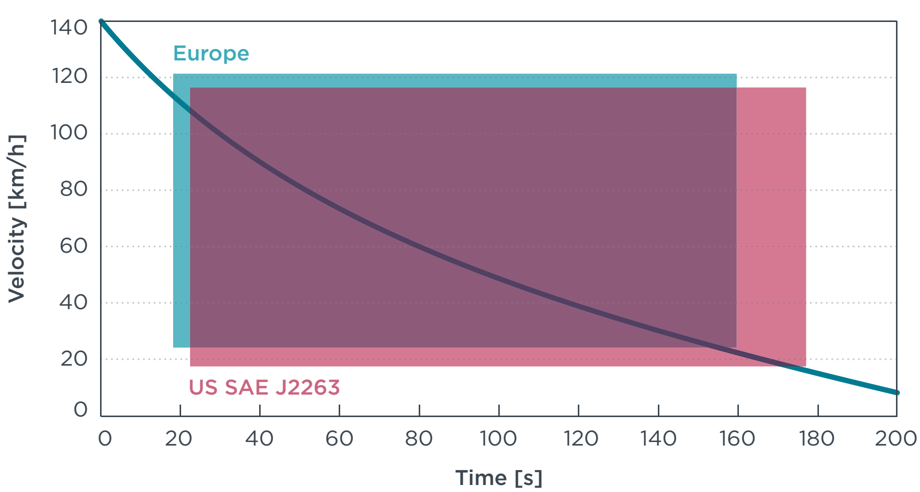

Figure 4. EU and U.S. velocity ranges of coastdown runs (EU interval averages).

Because driving resistance data derived from U.S. road loads are used in this study and compared with results from European data sources (see Section 2.4), the impact of the differences in the coastdown velocities on the derived road loads was assessed. Table 2 summarizes the main results. An average C segment vehicle with a characteristic coastdown velocity-over-time behavior was chosen. Both the EU and U.S. SAE J2263 methodologies were applied, and two different sets of road load parameters were calculated. From that the total driving forces at three base points (0, 60, 120 km/h) were computed and compared to each other.

Table 2. Effects of differences of velocity ranges on derived road load coefficients and total driving forces

Velocity range	Units km/h	EU 120–20	U.S. SAE 115–15	delta EU/U.S.-1
f0 (A)	N	122.2	120.4	
f1 (B)	N/(m/s)	-0.443	-0.207	
f2 (C)	N/(m/s)^2	0.442	0.436	
F @ 0 km/h	N	122.2	120.4	**+1.5%**
F @ 60 km/h	N	237.7	238.0	**-0.1%**
F @ 120 km/h	N	598.6	597.5	**+0.2%**

The observed difference in forces at 60 km/h and 120 km/h is marginal. The highest deviations occur near zero speed conditions (pure rolling resistance), but with just 1.5% higher forces using the EU methodology compared to the U.S., the agreement between both approaches is very good even at this extreme measurement point.

With regard to the low impact of the coastdown's vehicle velocity range on the derived road load parameters, it can be concluded that

- U.S. road load data can be used for comparisons with driving resistances of the European fleet without systematic errors, and
- the deviations between official and real-world CO_2 emissions are not due to insufficient velocity ranges of the coastdown procedure; rather, the main problems arise from imprecise testing conditions, such as modifications of the vehicle body, selection of tires, wheel alignment, road surface, weather, etc.

1.3 SENSITIVITIES OF DRIVING RESISTANCE VARIATIONS ON CO_2 EMISSIONS

The driving resistance forces are the main driver of the power and CO_2 emissions of a vehicle. The shares of the different types of forces depend on the actual driving conditions in terms of velocities and accelerations; road gradients are not considered here. The sensitivities of varying driving forces to fuel consumption (FC) and CO_2 emissions can be determined by vehicle measurements, or more easily and quickly by simulations applying adequate vehicle models.

Table 3. Impact of variations in mass, aerodynamic drag and rolling resistance on CO_2 emissions in WLTC (all data without secondary mass effects or adjusted engine performance)[3]

Technology category	-10% mass*	-10% rolling resistance	-10% aero drag
Gasoline – Current combustion engine	-3.0%	-1.2%	-2.5%
Gasoline – Advanced combustion	-4.3%	-1.7%	-3.3%
Gasoline – Advanced hybrid	-3.6%	-2.3%	-4.1%
Diesel – Current combustion engine	-3.6%	-1.4%	-2.6%
Diesel – Advanced combustion	-3.9%	-1.4%	-2.8%
Assumed fleet average (2020 mix)	**-4%***	**-1.5%**	**-3%**

**-4% total mass effect splits up to -2.5% acceleration and -1.5% rolling resistance*

Two vehicle emission simulation models were applied for such investigations: (1) the data visualization tool (DVT) by the automotive service provider Ricardo (Kasab et al., 2013), and (2) the passenger car and heavy duty emission model (PHEM) by Technical University (TU) Graz (Kühlwein et al., 2013). Both models were run with the latest Euro 5 emission maps. Table 3 represents the averaged results from both models for WLTC cycle simulations and medium vehicle sizes representing fleet averages. Current and advanced gasoline and diesel propulsion systems were taken into account, resulting in slightly higher sensitivities of the more advanced technologies. Altogether, at a 2020 technology mix perspective, the highest sensitivities were found for mass variations with 4% emission improvement by 10% reduction. Under the WLTC conditions the mass effects subdivided with 2.5% caused by forces during acceleration phases and 1.5% caused by changed rolling resistances, which show a proportional dependency on vehicle mass. Sensitivities of aerodynamic drag are a bit lower with 3% FC/CO_2 per 10% change, followed by rolling resistance with a 1.5% impact (without mass changes).

The data in Table 3 do not include secondary mass effects and do not reflect the positive effects of adjusted engine performance. The "secondary mass effect" occurs because a general mass reduction of an existing vehicle model allows for further replacements of heavy parts by downsized lighter ones, for example smaller brake disks or suspension systems, which lead to a further reduction of the vehicle's total weight. In addition, drivetrain components such as the engine and gearbox can be replaced by smaller variants while maintaining comparable vehicle acceleration performance compared to the original vehicle of higher mass.[4] This substitution further decreases the total mass and allows propelling the vehicle at the smaller engine's higher efficiencies.

3 Note that CO_2 emissions are not proportional to a vehicle's total road load as the engine also has to provide energy for "zero power output," which is energy for nonpropulsion processes such as friction of powertrain components (bearings, pistons, control, etc.), charge cycle work (engine timing), accessories (oil pump, water pump, alternator, power steering pump) and process parameters (mixture, firing angle). The energy consumption of these processes increases with engine speed but is not linked to the "effective engine power" propelling the vehicle. The "zero power output" can also be interpreted as the y-intercept of the "Willans lines." The required "zero power" for diesel engines normally is a bit lower than for gasoline because of the higher engine efficiency. Advanced engine technologies require lower "zero power output" and have consequently higher $\delta CO_2/\delta F$ sensitivities.

4 The top speed of a vehicle is mainly determined by engine power and aerodynamic drag. Hence, a reduction of the engine power with decreased vehicle mass at unchanged aerodynamic drag will lead to a reduction of the vehicle's maximum velocity. This reduction of the vehicle's performance should be taken into account for vehicles and markets where the maximum velocity is a relevant sales argument and could be an impediment for achieving a secondary mass effect.

Looking at the 2025 horizon with its restrictive CO_2 targets, more flexible and automated production processes, and drivetrain calibration procedures, it can be expected that vehicle manufacturers will design future engines around the specific performance requirements for each future vehicle, including anticipated reductions in vehicle mass. Just as today, the discrete number of available engine sizes means that some vehicles will slightly over- or under-perform the desired performance goal, but the average impact of discrete engine sizes on overall performance should be unchanged. Thus, for a proper assessment of CO_2 savings a constant level of vehicle performance is assumed, anticipating these future developments and the resulting secondary mass effects. The CO_2 saving potential of these secondary weight and engine size reductions has been assessed to be an additional 3% reduction in CO_2 emissions for each 10% reduction in vehicle weight (Kollamthodi et al., 2015).

1.4 VEHICLE SEGMENTS

The assessments of driving resistances within this study resulted in descriptive figures related to the total cars' fleet averages. Furthermore, the most relevant vehicle LDV segments on the European market were analyzed individually. These more detailed numbers are important for the interpretation of historical trends, as the fleet averages are influenced not only by technical modifications but also by market displacements among the segments. For example, in the past small sport utility cars (J segment) have been rapidly growing in the EU market, leading to significant reductions of mean weight and aerodynamic drag within the J segment, but at the same time increasing the total cars' fleet averages of these key parameters.

Table 4. European LDV categories examined in this study (maximum laden mass: <3500 kg)

LDV segment	Euro Car specification	Top 10 models on EU market 2013
A	Mini cars	Fiat 500, Fiat Panda, VW Up!, Renault Twingo, Toyota Ago, Smart Fortwo, Hyundai i10, Peugeot 107, Ford Ka, Citroën C1
B	Small cars	Ford Fiesta, Renault Clio, VW Polo, Opel Corsa, Peugeot 208, Toyota Yaris, Škoda Fabia, Citroen C3, Seat Ibiza, Fiat Punto
C	Medium cars	VW Golf, Ford Focus, Opel Astra, Audi A3, Škoda Octavia, BMW 1-class, Renault Mégane, Dacia Sandero, Mercedes A-class, Renault Scenic
D	Large cars	BMW 3-class, VW Passat, Mercedes C-/CLA-Class, Audi A4, Opel Insignia, Peugeot 508, Ford Mondeo, Audi A5, Škoda Superb, Volvo V60
E	Executive cars	Mercedes E-class, BMW 5-class, Audi A6, Volvo V70, Jaguar XF, Volvo XC70, Audi A7, BMW M5/M550, Volvo S80, Lancia Thema
J	Sport utility cars	Nissan Qashqai, VW Tiguan, Nissan Juke, Dacia Duster, Kia Sportage, Renault Captur, Hyundai ix35, Audi Q3, Ford Kuga, BMW X1
Vans	N1 III (>1760 kg reference mass)	Ford Transit, Mercedes Sprinter, VW T5, Renault Master, Fiat Ducato, Renault Trafic, Mercedes Vito, Ford Custom, Peugeot Boxer, VW Crafter, Citroën Jumper

Table 4 summarizes the most important LDV classes in Europe, which are the basis for the examinations of this study. The same classification was applied to the U.S. LDV fleet to make the U.S. trend results directly comparable to those derived from the European databases. Only the largest class of European vans (Class III, >1760 kg reference mass) was separately analyzed here, as vehicles of the two smaller van classes (Class I and II) can be considered as technically identical to regular cars already covered by the selected car segments. U.S. vans are defined as trucks by the U.S. vehicle definitions.

2. EVALUATED DATA SETS

Some extensive databases were evaluated to derive the most up-to-date averaged driving resistance parameters for both the complete LDV fleet (car fleet only, if data for vans were not available) and broken out by individual vehicle segments (A to E, J and N1 III). Furthermore, the latest 10-year trends for each of the three parameters (mass, rolling resistance, aerodynamic drag) have been quantified for the EU market. In cases where European trend data were not available, for example for tire rolling resistance, alternative data from the U.S. emission certification data bank were used, and the results were transferred to the EU situation as plausibly as possible.

2.1 ICCT INTERNAL DATABASE

ICCT has established a comprehensive internal database for the European market on technical LDV statistics, emission levels and registration volumes. The data are derived from a number of sources, including the European Environmental Agency (EEA), the United Kingdom Vehicle Certification Agency (VCA), the German Kraftfahrtbundesamt (KBA), IHS-Polk, automotive magazines and auto manufacturers' and importers' associations, as well as information provided directly by manufacturers and suppliers. The data are regularly updated and aggregated results are published.[5]

Data used for this report from the ICCT internal data base were:

» numbers of registration
» mass in running order
» maximum laden mass
» segmentation of LDV fleet

All calculated European mass averages for both the total fleet and individual vehicle segments were volume weighted by the number of new registrations in the respective year.

2.2 KM77 DATABASE

km77.com[6] is a Spanish website that offers car reviews and services targeted at consumers interested in purchasing a vehicle. It contains a large collection of technical specifications of passenger cars in Europe (km77.com, n.d.). For this analysis, we used km77 data for the aerodynamic drag coefficients (C_d) and the frontal area (A_f) for all currently available vehicles. In addition, historic data about the past 10 years was taken from km77. Altogether, more than 2,000 complete data sets, including both C_d and A_f, came from km77.

5 See http://eupocketbook.theicct.org
6 http://www.km77.com

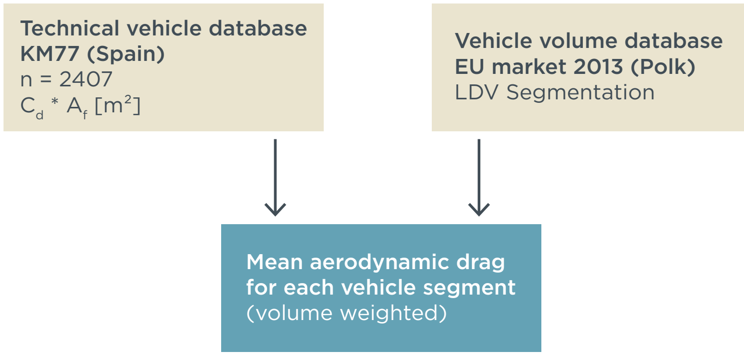

Figure 5. Scheme for the calculation of volume weighted and segment-specific aerodynamic drags (C_d * A_f).

C_d * A_f data were linked to registration volumes from the ICCT internal database, which also includes the necessary information about the attribution of individual vehicle models to segments. Hence, the calculations resulted in volume weighted averages for each of the specified vehicle segments. Besides C_d * A_f, the same procedure was applied to C_d and A_f separately.

It must be noted that the collection of the km77 database concerning aerodynamics is based primarily on announcements from manufacturers. These typically are more focused on top performing vehicle variants. Hence, it must be suspected that the distribution derived from km77 data is shifted toward lower aerodynamic drags and is not fully representative for the whole car fleet. These deviations have been taken into account by deriving a correction factor (see Section 3.3).

2.3 EUROPEAN TIRE MARKET DATABASE

A comprehensive tire database including more than 12,000 different makes, models and sizes provided by Lanxess (personal communication, November 2014) was evaluated. As shown in Figure 6, unweighted average rolling resistance coefficients (RRC) were calculated for each tire specification from the rolling resistance label attributes. The weighted rolling resistance averages of each label class were provided by the European Tyre and Rim Technical Organisation (ETRTO, personal communication, November 2014). The tires were specified by five parameters: width, height, rim diameter, load index and speed index.[7] On the other hand, the allowed tire specifications were determined for the 10 most sold vehicle models of each vehicle segment. These weighted vehicle model specifications were combined with the averaged RRC resulting in volume weighted vehicle segment averages.

7 Tire parameters typically are specified as tire width (mm), height to width ratio (%), rim diameter (inches), load index (two- or three-digit code indicating the maximum weight load per tire), and speed index (one-letter code indicating the maximum vehicle velocity).

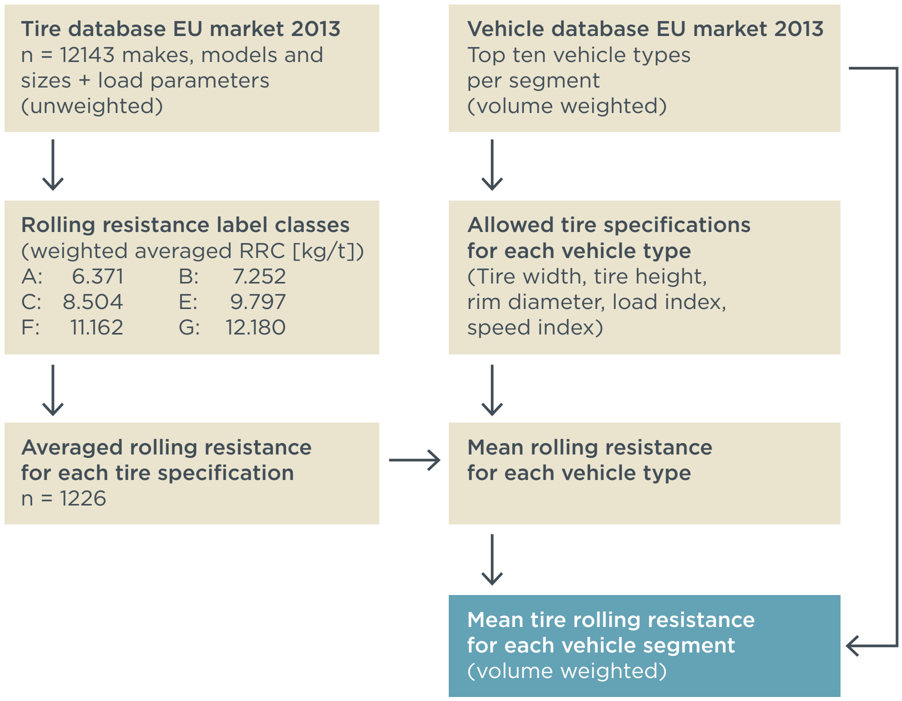

Figure 6. Scheme illustrating the derivation of volume-weighted and segment-specific tire rolling resistance coefficients. (RRC label class D not applied for LDV tires.)

Data on European tires' rolling resistances were available only for 2013. Hence, no temporal tendency could be derived from this methodology.

Note that also parts of the driveline, including wheel bearings, the differential, and parts of the gearbox, are rotating during the coastdown of a vehicle. They also contribute to the total rolling resistance and must not be neglected (see Section 3.2).

2.4 US EPA TEST DATABASE

The road load coefficients describe the complete driving resistance behavior of a vehicle over the relevant velocity range. These data can be very useful in detecting LDV's driving resistances and in particular their temporal development. However, in the EU, the official type-approval road load data sets are not publically available. In contrast, the respective data sets from the US EPA certification database are easily accessible via download from a publicly available website (EPA, 2014). Indeed, the focus of this study is on the European situation, but valuable conclusions can be drawn from the U.S. data and compared, or even transferred, to the conditions in Europe.

With an appropriate approach, it is possible to recalculate the driving resistance parameters RRC and aerodynamic drag if the underlying test mass of the vehicle is known. However, because the RRC itself depends on the vehicle's velocity (dependency up to a fourth exponent), the derivation cannot be done with 100% accuracy. The f1 (B) and also the f2 (C) coefficients include parts of the rolling resistance. The problem with the f1 (B) coefficient can be resolved by applying the following methodology, as described in Figure 7:

1. Applying a new quadratic fitting curve with only f0 (A) and f2(C) coefficients to each set of road loads.
2. Translating the two new coefficients into RRC and aerodynamic drag by applying the basic formulae of the driving forces, assuming that:

$A_{new} = F_{RR}$
$C_{new} = F_{AD} / v^2$

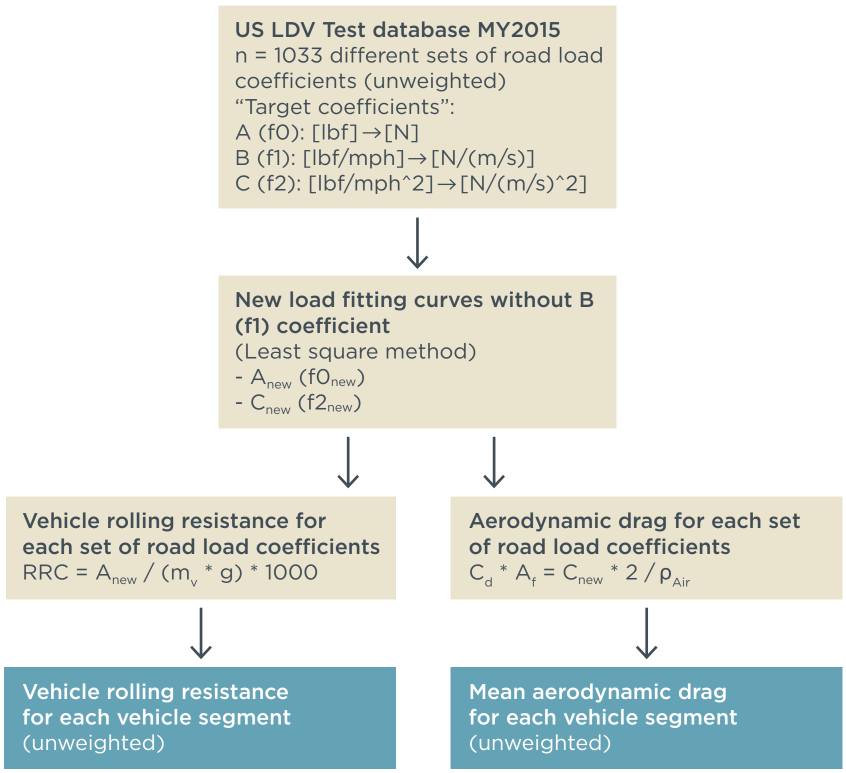

Figure 7. Scheme for calculating the segment-specific rolling resistance coefficients and aerodynamic drags from the US EPA LDV certification database.

The methodology applied does not yet eliminate the effect that the new f2 (C_{new}) coefficient includes some minor parts of the rolling resistance because of the high speed dependencies of the RRC, in particular at high vehicle velocities. Altogether this leads to slight underestimations of the RRC and to slight overestimations of the aerodynamic drag. This is particularly the case for soft tires with low load indexes and high rolling resistances, which are normally not the first choice tires for manufacturers to be employed at certification coastdown runs.

However, the temporal trend of these derived values is much less susceptible to methodical errors than the absolute figures. Thus, highly accurate insights into the temporal developments of the driving resistances in the U.S. market could be gained for fleet and vehicle segment averages.

3. TRENDS AND CURRENT SITUATION

This chapter describes fleet averaged values of the driving resistance parameters mass, rolling resistance and aerodynamic drag. The observed 10-year trends and the current averages for new vehicles are described in the following sections.

3.1 MASS

Vehicle masses averaged for vehicle segments and volume weighted were extracted from the ICCT internal database. They include mass in running order (mass iro) as defined at the EU level for the New European Driving Cycle (NEDC) and as used, for example, as entries in the Certificate of Conformity (CoC). The mass iro is the curb weight of the vehicle including spare wheel, on board tools and 90% filled fuel tank plus 75 kg for the driver and some basic luggage. Table 5 also includes the NEDC reference mass as used for the chassis dynamometer settings, which is 25 kg higher than mass iro, and the average maximum laden mass. It is obvious that segment mass averages for diesel vehicles are somewhat higher than those for gasoline vehicles. This is partly due to the fact that diesel engines in the EU are, on average, bigger and more powerful than gasoline engines, and can therefore be found more often in larger and heavier vehicles. In addition, the large differences in the J segment indicate that bigger SUVs are more often equipped with diesel engines than smaller ones.

Table 5. Average NEDC masses, maximum laden masses (for masses of extras see Appendix D)

Segment	Mass in running order (kg)	NEDC reference mass (kg)	Maximum laden mass (kg)
Diesel			
B	1224	1249	1658
C	1434	1459	1935
D	1625	1650	2126
E	1838	1863	2347
J	1688	1713	2195
N1 III	2026	2051	2800
Gasoline			
B	1150	1175	1564
C	1345	1370	1834
D	1578	1603	2057
E	1800	1825	2287
J	1415	1440	1870

The NEDC based test masses, shown in Table 5 as the reference mass, do not consider extra vehicle equipment or average payload. Hence, the official CO_2 emission tests are based on unrealistically low vehicle masses, and the test results systematically underestimate the real-world emission behavior. In contrast to the NEDC, the new Worldwide Harmonized Light Vehicles Test Procedure (WLTP), whose introduction into EU law is planned for 2017, will include more realistic test masses.[8]

8 The WLTP foresees testing for a low load and a high load vehicle version within each vehicle family. In terms of mass, this means that the lower boundary is a “test mass low” (TML) vehicle version without any extras, and the maximum extra equipment will be on board of the “test mass high” (TMH) version.

Assessments of the maximum and average masses for extras and payloads for the different engine types and vehicle categories are included in Appendix D of this report.

Figure 8 shows the temporal development of cars' mass fleet averages for the EU and the U.S. For the U.S. both volume (sales) weighted and unweighted data for cars according to the EPA classification were applied. More exotic vehicle models with relatively low sales numbers are heavier than the fleet average, and their amount in the total models' number has increased over the past 10 years, leading to a 0.5% per year higher increasing trend for the unweighted data. Furthermore, the U.S. data averages are depicted in two different ways of interpreting the car class: The EPA definition distinguishes between light SUVs, which are assigned to the car class, while heavier SUVs are identified as trucks and, hence, are not included in the cars' mass averages. On the other hand, the EU cars classification includes all types of SUVs, as long as the maximum laden mass is below 3500 kg. To ensure a better comparability to the European data, the U.S. data were regrouped according to the European car segmentation system (EPA, 2016).

Following the EU cars' classification, the absolute mass averages in the U.S. are clearly higher than in the EU. The main reasons for this deviation are:

- U.S. test masses include extra equipment and larger payloads than the NEDC mass in running order.
- Sales weighting results in lower averages than for unweighted data.
- The U.S. car fleet composition includes a higher share of heavy car segments.
- Within the individual car segments, U.S. models are on average heavier than EU models.

The 10-year trend is clearly increasing, although only slightly. An annual fleet average increment of 0.4% can be observed for the EU, which is in good agreement with the U.S. cars' development, where the assessment according to the EPA cars classification (without heavy SUVs) resulted respectively in 0.7% (unweighted) and 0.2% (sales-weighted data) increases per year. These slight increases reflect the trend of increasing shares of lighter SUV models being assigned to the cars category as defined by EPA. Including all SUVs in the calculation of the mass averages, in accord with the EU classification, reduces the unweighted trend to 0.1% per year.

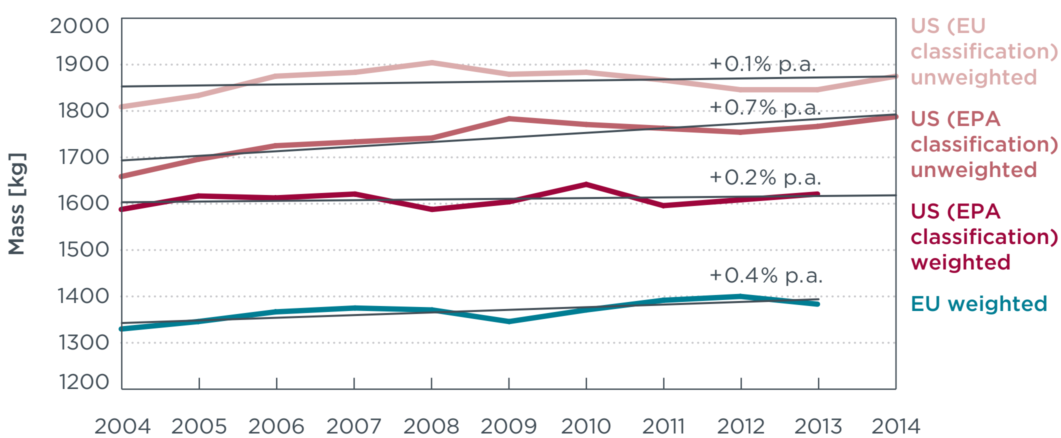

Figure 8. Cars' mass market averages: 10-year trend U.S. (test masses) and EU (mass in running order).

Table 6 indicates that the slightly increasing trend can be observed consistently for all relevant car segments except for SUVs (J segment), where the EU market has shifted to a higher number of smaller and lighter versions. However, for most segments the mass curve has flattened over the past 3–4 years (see also Appendix A), indicating that the trend of bigger vehicles in the market has been slowed and that mass reducing measures are not overcompensated any more by adding more extra equipment. The fact that the trend for the U.S. total car fleet average is lower than for most of the individual car segments suggests a slight shift toward smaller and lighter car segments has occurred over the past 10 years.

Table 6. Mass – 10-year trends of LDV segments

Segment	Annual average change	
	EU 2004–2013	U.S.* MY 2005–2015
Car fleet	**+0.4%**	**+0.1%**
A	+0.5%	n/a
B	+0.7%	+0.6%
C	+0.4%	+0.4%
D	+0.8%	+0.3%
E	+0.9%	+1.0%
J	-1.5%	0.0%
Vans	+0.4%	+0.6%

**U.S. fleet values are not sales-weighted, with car segmentation following EU criteria.*
The number of A segment models in the U.S. is too low to derive convincing trend data.

3.2 ROLLING RESISTANCE

Besides acceleration forces, the rolling resistances of a vehicle mainly determine the overall driving forces at low driving velocities, for example in urban driving. The tires' properties and their rolling resistance coefficients dominate the overall rolling resistance. Friction losses of the vehicles' drivetrain play only a minor role. Hence, major improvements can be achieved rather quickly by a simple replacement of mounted high resistance tires. Benefits can be achieved even for older vehicles and are under control of the vehicles' owners, rather than depending on manufacturers' decisions on the vehicle body structure, materials and equipment, provided that tire manufacturers are offering high-quality products on the market at reasonable prices.

The results of the analyses of the actual EU driving resistances are summarized in Table 7. Based on the evaluations of the tire databases, a good correlation between the load index of a tire and its rolling resistance label classification can be observed. A high load capability means higher stiffness and lower plasticity of the tire. Hence, there is less energy lost to material deformation and heat generation. The width of the tire shows no correlation with rolling resistance. On the contrary, larger and wider tires on the EU market are of slightly better quality and feature high load indexes and lower mean rolling resistance coefficients. Therefore, the data in the table show a continuous declining trend of RRC with increasing vehicle size, except for the C segment for which a higher share of low rolling resistance tires is already available.

Table 7. Average rolling resistance coefficients for tires and drivetrains in EU 2013

Segment	RRC tires (kg/t)	RRC drivetrain (kg/t)	RRC total (kg/t)
A	9.97	1.7	11.67
B	10.01	1.7	11.71
C	9.53	1.7	11.23
D	9.69	1.7	11.39
E	9.63	2.0	11.63
J	9.44	2.8	12.24
N1 III	9.36	1.7	11.06

Rolling resistances of the mechanical driveline must also be taken into account. Normally the gearbox is decoupled during the coastdown tests, which means that friction losses of rotating parts are restricted to the wheel bearings, the differential, and to those parts within the gearbox that are directly linked with the driveshaft. However, these losses are not negligible. Available data on driveline losses in open literature are rather poor. A report to the European Commission (Ligterink et al., 2014) suggests a measured rolling resistance of 9.9 N for each driven wheel and 2.3 N for each free-running wheel for a car of 1443 kg test weight. This corresponds to a 14% share in total rolling resistance for a singe-axle driven LDV and a 21% share for a two-axle driven vehicle, respectively.

Trend data on tires for the European market were not available. Alternatively, the 10-year data derived from the U.S. emission certification and road load database (EPA, 2014) were used, as shown in Figure 9. These absolute values represent the total rolling resistance, including tires and drivetrain, and are somewhat lower than the current EU market average. This is likely due to the deployment of high performance tires with low rolling resistances for certification purposes, which is not reflected by market average data. However, the temporal trend should not be impacted by such absolute offsets. Note that the green triangle in Figure 9 labeled EU Total RRC represents the sum of driving resistances for average market tires and mechanical parts.

The linear regression of the U.S. data results in an average annual decline of 1.3%. Note that sales data are not available for the individual configurations in the U.S. road load data, so the regressions are related to unweighted data, which is to say every individual vehicle model has the same weighting. As discussed previously for mass (see Section 3.1), there is a recent trend for increasing numbers of high-performance cars with low sales volumes. These vehicles will also have higher rolling resistance tires, thus the real (sales-weighted) trend should be greater than 1.3% per year. This could also partially explain the observed flattening of the U.S. curve of rolling resistances since MY 2011. Compared to the trend in the U.S., strong legal requirements in the EU will most likely surpass this observed progress in the future (see Section 4.2).

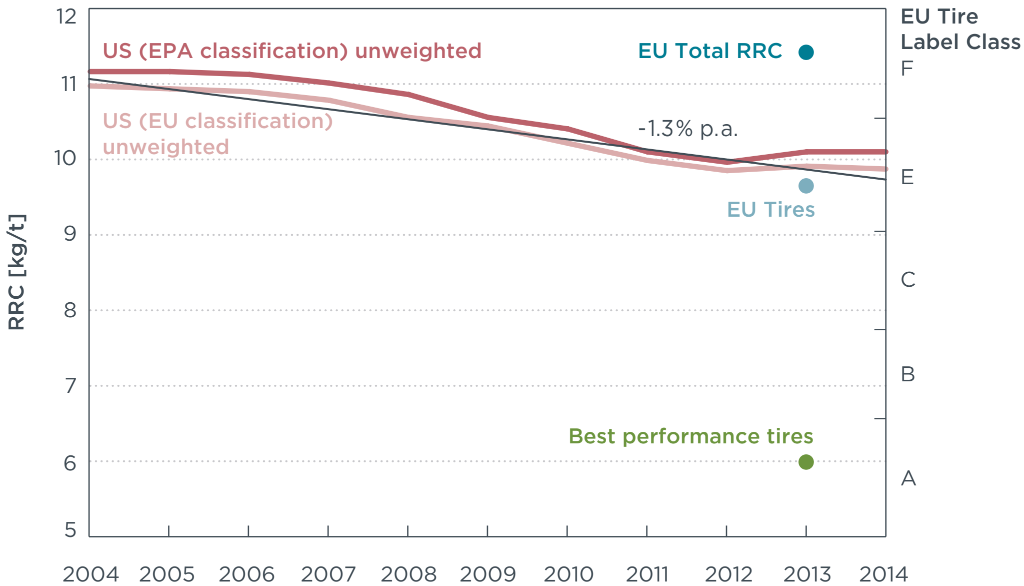

Figure 9. Rolling resistance: 10-year trend U.S. car fleet (whole vehicle), EU classification with all SUVs, EPA classification without heavy SUVs, and status quo EU (total and tires only).

The vehicle segment-specific trends in the U.S. for rolling resistances are shown graphically in Appendix B and summarized as annual average relative changes in Table 8. The positive trend is consistent over all segments and tire sizes. The C segment shows the most dynamic development (1.9% per year compared to 1.3% per year for the total fleet), which is in good agreement with the assessment of the European tire databases, resulting in disproportionately low rolling resistances of tire sizes matching the C segment. Also in good agreement with EU results is the worst performance of the smallest tires (B segment, in the case of U.S. data) with only a 0.3% annual decline. This implies that the tire industry (and applying car manufacturers) still focuses its research and development activities on bigger tires, which are also more expensive, while the potential for improvements of smaller tires is not yet fully exploited.

Table 8. Rolling resistance – 10-year trends of LDV segments

Segment	Annual average change U.S.* MY 2005–2015
Car fleet	**-1.3%**
A	n/a
B	-0.3%
C	-1.9%
D	-1.3%
E	-1.3%
J	-1.4%
Vans	-1.6%

** Unweighted data. Results for the A segment are not significant because of low relevance in the U.S.*

3.3 AERODYNAMIC DRAG

The aerodynamic shape and structure of a vehicle's body and chassis, represented by C_d, and its frontal area, represented by A_f, both contribute to its total air resistance ($C_d * A_f$). The volume-weighted fleet segment averages in EU 2013, as shown in Table 9, show a slightly decreasing trend of C_d with increasing vehicle size among the classic body shapes of segments A to E. This reflects both the fact that it is easier to manage airflow over a larger vehicle and the latest efforts of the manufacturers to employ sophisticated improvements of individual body parts, such as wheel cases, which are first applied to higher vehicle classes where the additional cost associated with these measures is less relevant in relation to the total car's price. The increase of the frontal area from the A to E segments is offset by decreasing C_d values leading to rather similar total aerodynamic drags ($C_d * A_f$) over these segments. As expected, SUVs show the worst aerodynamic behavior with highest C_d and A_f values among all passenger car classes. The aerodynamic drag coefficient of modern light commercial vehicles (N1 III) is not much worse than those of cars, but the larger frontal size results in higher total air resistance.

Table 9. Average aerodynamic drag values in EU 2013

Segment	C_d	A_f	Aerodynamic drag $C_d * A_f$	
	from database (-)	from database (m^2)	from database (m^2)	adjusted (+11%) (m^2)
A	0.33	2.09	0.68	0.76
B	0.32	2.11	0.67	0.75
C	0.30	2.28	0.70	0.77
D	0.29	2.24	0.65	0.72
E	0.29	2.40	0.69	0.77
J	0.35	2.50	0.88	0.98
N1 III	0.34	4.06	1.38	1.53

Data from public sources about aerodynamics cannot be regarded as representative for the total fleet. That is because (1) manufacturers publish data mainly for vehicles with above-average aerodynamic performance, and (2) published data often are optimized to a special version of a vehicle model and cannot be seen as representative for the whole vehicle family. Therefore, mean European aerodynamic drag values taken from the km77 database do not provide a fully representative picture, and the results derived from that database need to be corrected in order to determine the real fleet averages. Car models being offered with an identical vehicle body on both markets in the EU and the U.S. were analyzed in greater depth. Those car models with coincident aerodynamic drag data from the European km77 database and road load data from the US EPA data base were identified.[9] The comparisons of the aerodynamic drag values between the U.S. data and the km77 data for those car models resulted in 11% higher values, on average, in the U.S. Assuming that these quantified differences are representative for all vehicles included in the km77 database, a fleet average correction factor of 1.11 was derived for km77 data. These adjusted values are presented in the far right column of Table 9.

9 This approach circumvents the "natural" deviations regarding car sizes between the U.S. and EU car fleets.

Figure 10 depicts the 10-year trends of the unweighted total car fleet average aerodynamic drag in the U.S., derived from the U.S. road load data, and in the EU as derived from the EU databases (volume weighted and uncorrected). The U.S. trend, according to the EPA car classification, is on a rather stable level with only slight deviations around the year 2010. Significant improvements can be observed for the SUV class (J segment in Table 10), which also are reflected by the downward trend of the total car fleet when considering all car fleet SUVs, as is done by the EU classification. However, as the total aerodynamic drag consists of both the aerodynamic characteristics and the frontal area of the vehicle, it cannot be concluded distinctly if the negative trend for SUVs is caused by real aerodynamic improvements or if it is just an implication of the market shift from bigger to smaller SUV models. Again, the trend for weighted averages could be slightly different from the unweighted averages, but in case of aerodynamic drag, it is not clear if or how the more exotic cars differ systematically from the cars fleet average. Aerodynamic drag values in the EU are slightly but very consistently rising. This small effect is mainly caused by volume shifts among the vehicle segments, in particular, the demand for small SUVs (J segment) has risen considerably. This has led to an overall deterioration in the aerodynamic drag balance for the total car fleet. Compared to rolling resistance, improvements in aerodynamics are technically more demanding, as they are influencing the structure of chassis and body, and often are linked with other negative functional effects.

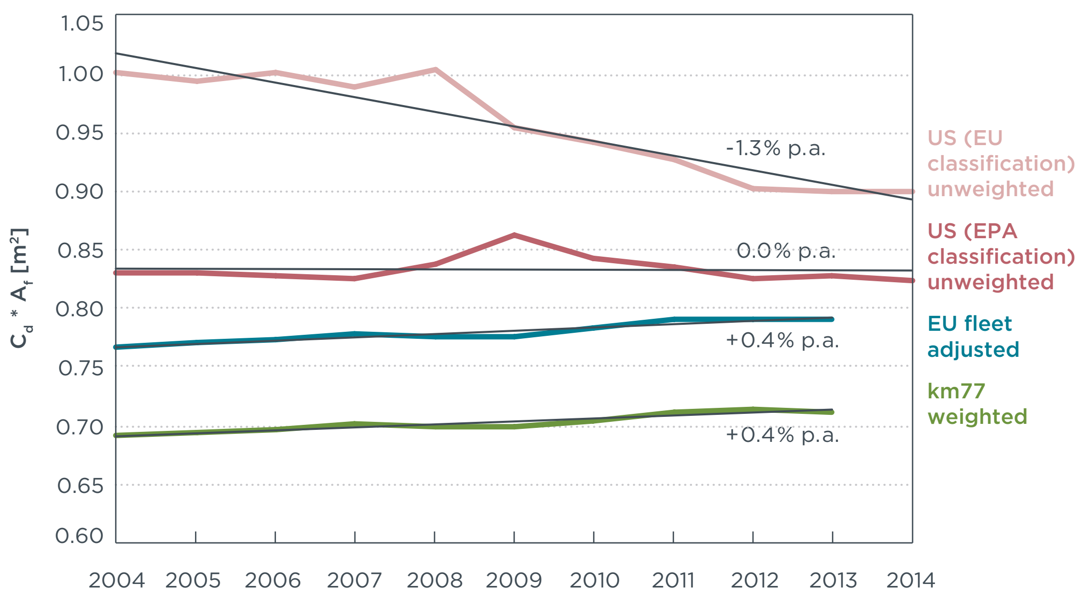

Figure 10. Aerodynamic drag – 10-year trend of cars' fleet averages, showing U.S. unweighted values based on EU classification with all SUVs, U.S. unweighted values based on EPA classification without heavy SUVs, select weighted EU data from the km77 database, and EU values adjusted to realistic fleet averages.

The EU databases in km77 consistently show almost no change over the past 10 years for the most relevant vehicle segments (see Table 10 and Appendix C). Only the J segment features clear improvements, but this is primarily because of the increased sales numbers of smaller SUVs.

Table 10. Aerodynamic drag – 10 year trends of LDV segments

Segment	Annual average change	
	EU 2004–2013	US* MY 2005–2015
Car fleet	**+0.4%**	**-1.3%**
A	+0.3%	n/a
B	+0.0%	-0.3%
C	-0.1%	-0.8%
D	0.0%	-0.9%
E	+0.5%	-0.3%
J	-1.6%	-1.8%
Vans	n/a	-0.5%

* *Unweighted model data*

Improvements in aerodynamic drag coefficients for segments A to D are observable on the order of 0.5% per year, but are almost fully offset by increased frontal areas. Figure 11 shows this contrary trend for the fleet averages.

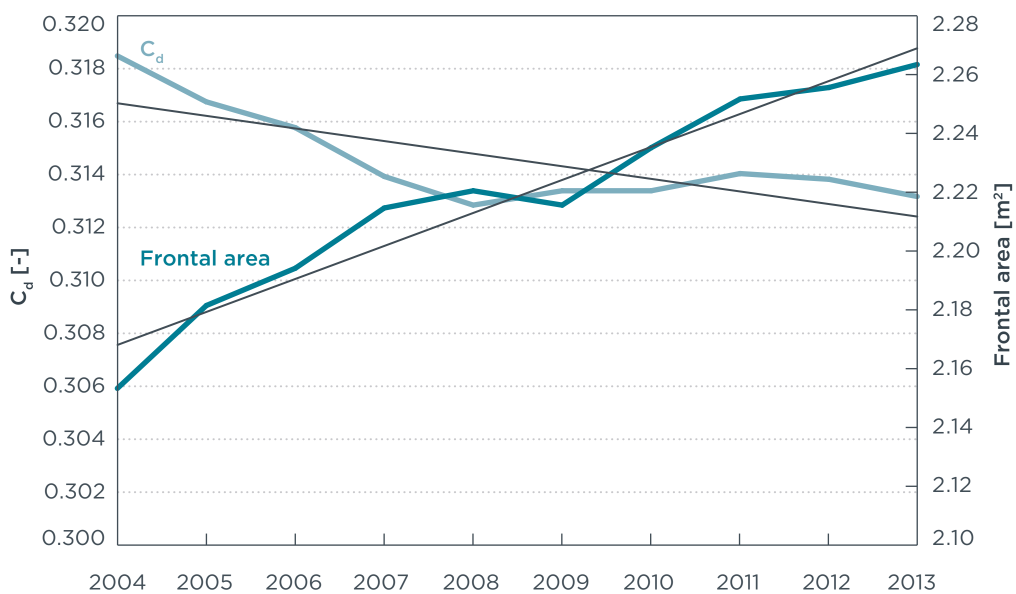

Figure 11. 10-year trends for EU aerodynamic drag coefficients and frontal areas of new passenger cars – Fleet averages using data from km77 database and not adjusted to realistic fleet averages.

4. SCENARIOS FOR 2025

In the following, two scenarios were developed for the development of the main driving resistances. Both scenarios are based on the 10-year trend data and the current market averages described in Chapter 3 and the best-in-class analyses described in this chapter. Furthermore, additional regulatory measures were explored, which are of particularly relevance for the tires' rolling resistances, and recent technology developments were considered. Scenario bands were derived covering the technical potential for the 2025 time frame. The lower, more pessimistic border of these bands, scenario 1, is based on the historical data and the actual best-in-class performance. The upper, more optimistic border, scenario 2, is based more on the maximum technical feasibility.

The projections presented in this chapter are solely based on the technical feasibility within the next 10 years. Material or production costs and other economic parameters have not been considered for this report, but will be the subject of future assessments.

4.1 MASS

Mass reductions can be achieved by

- replacement of heavy materials with lightweight substitutes, such as high-strength steels, aluminum, highly loadable plastics and carbon fiber carbon composites (CFC)
- computer-aided design and material-saving production processes
- waiver of equipment

However, reducing mass is a complicated endeavor, as the whole vehicle with all its parts needs a complete analysis and revision. Currently such a full re-engineering can be observed in some vehicle models, mainly of higher end car segments, but still mostly at rather low production volumes (with some exemptions) and not yet significantly influencing the total fleet averages. High-strength steel is rapidly gaining market share and achieving economies of scale, but parts produced from other lightweight materials at the beginning of the process in relatively low production numbers are causing higher costs compared to using standard materials (Kollamthodi et al., 2015). The conversion of production processes, which is to say from rather static modular to more flexible concepts, has been initiated. Deleting equipment is not an acceptable way to reduce weight, as it often is interpreted by consumers as a lack of comfort. But the introduction of rather puristic and stylish car models can be seen on the EU market, fulfilling the demands of particularly cost-aware consumers. Meanwhile, the converse trend of adding extra equipment – both mandatory and comfort-determined devices – is ongoing and negates much of the hard-earned weight savings gained on the material mass side.

Recent developments in computer simulations are making it possible to simultaneously optimize the material, shape, and thickness of every part on the vehicle. This integral construction approach was never before possible. Previously only individual parts, often from different suppliers, could be mass optimized, but the interaction of all vehicle parts could not be simulated and optimized concurrently. Such a holistic simulation approach can reduce tolerances required for safety and cut down material input.

The EU mass trend for passenger cars has been increasing slightly at an average of 0.4% per year over the last 10 years. However, when observing only the past 3–4 years, stagnation or even a slight reversal of the trend can be seen. Especially manufacturers with relatively high average masses in the past, like PSA (Citroen and Peugeot), are catching up with the latest technical developments and are achieving big steps in weight reduction when issuing new car generations. The technical potential exists for further significant mass reduction. But at the same time, high development and investment costs are inhibiting a fast implementation to high-volume models. The time it takes to change current production processes is also slowing implementation. A European vehicle generation's lifetime is 7.25 years, on average, depending on the vehicle segment (see Figure 12). High volume vehicle models have the shortest generation lifetimes (6.6 year average for the C segment), while smaller and larger classes show much longer intervals for a technical revision. A segment generation lifetimes average 8.4 years; it is 11.5 years for MPV and N1 III models. The weight reductions achieved in current new model generations are generally between 50 kg and 80 kg, although some innovative exemption models show even higher achievements.

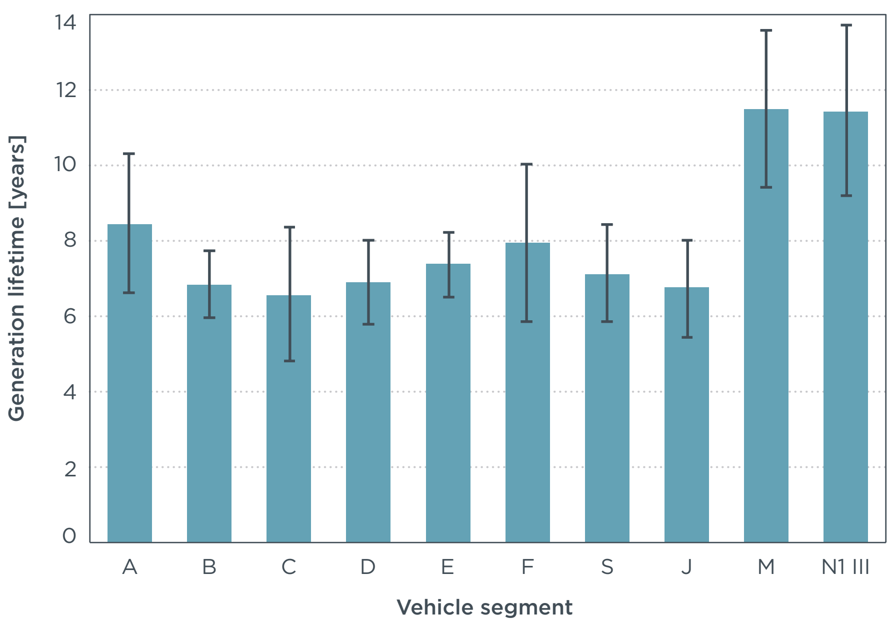

Figure 12. Average generation lifetimes of European light-duty vehicle models for the top10 models sold in 2014 for each vehicle segment. Error bars represent the standard deviation of evaluated models for each segment.

The identification of the best performing vehicles currently on the market can give an impression about the technical potential of weight reducing measures, assuming that some vehicle models are technically more sophisticated than competing vehicles within the same segment. Table 11 compares the total average masses of each segment in 2013 with the best performing model within the top 10 sellers. On average, a difference of 10% was found. It must be considered that these deviations are partly due to different levels of equipment. For example, in the C segment the Dacia Sandero has been identified as having the lowest weight, but it is known to be a rather cheap and simplistic model with older technology and less comfort equipment. On the other hand, the restriction to the top 10 models keeps exotic models with very low numbers from determining the results, but also could dismiss the most progressive models with the most innovative technology, such as those from niche manufacturers.

Table 11. Mass – best performing vehicle models within the 10 best sellers of each vehicle segment

LDV segment	Average mass iro of top 10 models (unweighted, kg)	Best performing model	Model's lowest mass of top 10 best sellers (kg)	Deviation between top model and segment average
A	948	Smart Fortwo	838	-12%
B	1141	VW Polo	1105	-3%
C	1368	Dacia Sandero	1097	-20%
D	1631	BMW 3 Series	1560	-4%
E	1861	Volvo S80	1715	-8%
J	1496	Renault Captur	1226	-18%
N1 III	2054	Renault Trafic	1833	-11%
Average				**-10.8%**

Two scenarios were derived for the 2025 horizon from these current best-in-class analyses:

Scenario 1. For the less ambitious scenario, the average 10% difference for today's best performing vehicles compared to the segment-specific fleet averages was applied, assuming that today's best available weight saving technologies will be taken over by all relevant high-volume manufacturers within the next 10 years.

Scenario 2. The more ambitious scenario assumes a stronger dynamic in applying lightweight materials and reflects the whole bandwidth of possible technical measures being used to optimally reduce the mass of a specific vehicle model. Based on the fact that some models already have achieved 14% or larger weight reduction between two generation types, and the availability of two redesign cycles for some vehicles by 2025, a general 20% weight reduction was determined (Figure 13). This also reflects the currently observed maximum deviation between a best-in-class model and the average of the respective vehicle class (Dacia Sandero in C segment).

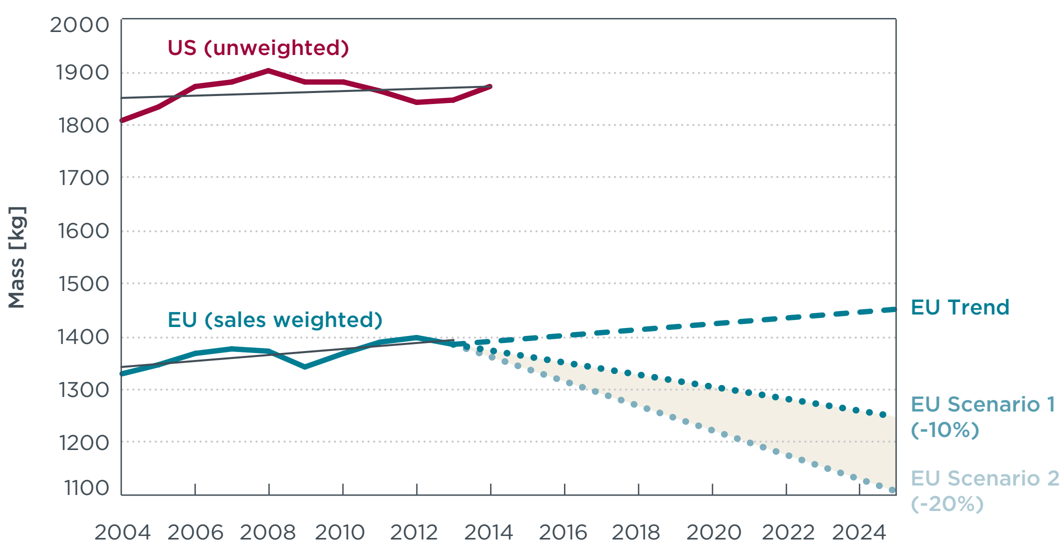

Figure 13. Projected mass market averages for cars, based on 10-year trend U.S. (test masses) and EU (mass in running order) and technical projections EU to 2025.

4.2 ROLLING RESISTANCE

In comparison to mass reduction and aerodynamic resistance improvements, a reduction in tire rolling resistance can be achieved relatively quickly and with little effort. Tires with very low rolling resistance coefficients already have been developed and are available on the market for all tire sizes. Hence, they can be applied to all existing vehicles to achieve a large effect over the whole fleet, without the need to redesign the vehicle itself. Exchanging tires can be done easily, and the effect is left more in the hands of the vehicle owners and suppliers rather than vehicle manufacturers. The effort required to develop new rubber compounds and optimized structures is relatively small, and the higher prices of a high quality product are reasonable, measured against the fuel saving effects.

The future development of rolling resistances of tires on the European market until 2025 will be strongly affected by three regulatory measures:

1. the prohibition of tires with poor rolling resistance
2. the tire labeling scheme
3. the introduction of the WLTP as new type-approval procedure.

Prohibition of tires

First step, 2015: The European Commission bans tires with a poor rolling resistance performance from the market. The worst tires for LDV with G label (RRC above 12 kg/t) already are no longer eligible to be mounted on a new vehicle per EC/661/2009 (European Commission, 2009a). This leads to a shift and a more narrow distribution of RRC of market tires, as can be observed at Figure 14 when comparing the blue line, which represents actual market data in 2013, with the brown line showing the derived distribution curve for 2015.

Second step, 2019: Prohibition of F labeled tires (RRC above 10.5 kg/t) will follow from September 2018 onward. This second measure will lead to a further distinct shift of the rolling resistance distribution until 2019 including A, B, C and E labeled tires only, as shown by the green line in Figure 14. This regulatory control measure is highly effective and could be extended easily by further legislative acts to the next lower tire label classes (E, C) in future.

Tire labeling

With the introduction of a tire label in the EU in November 2012, per EC/1222/2009 (European Commission, 2009a), the consumer became directly informed about the main quality characteristics of these products. The label includes quality classes on rolling resistance, noise and wet grip. The boundaries of the rolling resistance classes are shown in Figure 14. Experience with other labeled products, like whiteware, shows that it takes a couple of years until consumers are sensitized to the existence of the label and to the advantages it gives the buyer when purchasing a low energy consuming product. It is expected that a buyer of a new car will have a choice also on the type of tires, not only on tire sizes, in the future. Manufacturers will therefore react based on client demands and mainly offer low rolling resistance tires.

Introduction of WLTP

With the introduction of the WLTP as the new type-approval procedure for LDVs in the EU, which is foreseen for 2017, the certified values for CO_2 emissions will be vehicle specific and directly linked to the real driving resistances of each individual vehicle sold. This procedure will lead to a more realistic declaration (e.g., entries in the Certificate of Conformity, or CoC) and to more transparency compared to the current NEDC rules, where the type-approval CO_2 emissions of all versions of one vehicle family are based on the same driving resistances as specified by the test vehicle used for the official coastdown run. This means that the tires actually mounted on a new vehicle by the manufacturers currently have no impact on the vehicle's certified CO_2 values. As fuel consumption is an important consideration for potential clients, manufacturers will be forced under the WLTP to narrow the range of tire models they offer by focusing on high quality products.

It is assumed that consumers' sensitization to the fuel- and money-saving effect of low rolling resistance tires related to the tire labeling and the more realistic declarations under WLTP will have a strong impact on the further development of the market. The worst tires, with E labels, will no longer be in demand and will disappear, even without additional legal measures. The purple curve in Figure 14 indicates the expected RRC distribution in 2025.

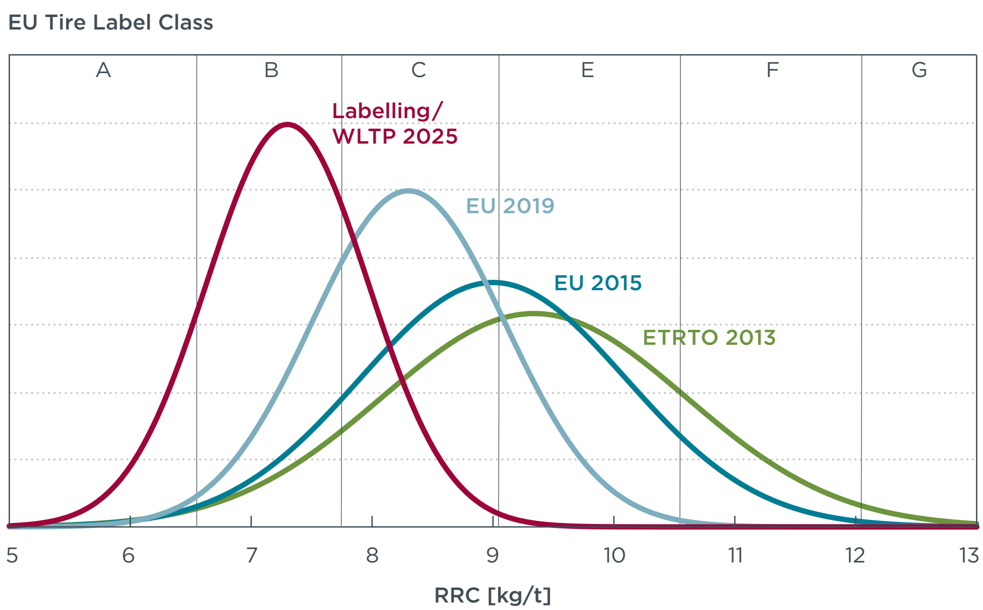

Figure 14. Projected development of tire rolling resistance distribution in the EU market for original equipment tires.

Table 12 summarizes current and predicted average tires' rolling resistance coefficients. Until 2025, with the prohibition of F and G labeled tires, a more sensitive behavior of the consumers in buying low labeled tires and the introduction of the WLTP type-approval standards, a 22% reduction (from 9.34 to 7.3 kg/t) can be expected, which is a year-on-year drop of about 2%. Most original equipment tires in 2025 will be B labeled, probably still leaving some potential for exceeding improvements toward A labeled tires, which are already on the market, and beyond that by applying new rubber compounds and optimized tire structures.

Table 12. Current and expected average tires' rolling resistance coefficients in the EU

Normal distributions	ETRTO[10]	EU Legislation / Labeling / WLTP		
	2013	2015	2019	2025
Mean (kg/t)	9.34	9.0	8.3	7.3
Stddev (kg/t)	1.26	1.1	0.8	0.7
delta		-3.6%	-11.1%	-21.8%
annually		-1.8%	-1.9%	-2.0%

The technical development beyond 2025 will most likely lead to tires with RRC below 6 kg/t. This could enable a further reduction of the technical optimum RRC of another 10%.

The availability of data on rolling resistances of the driveline (wheel bearings, differential, and gearbox parts connected with the driveshaft) is rather poor. For the sake of simplicity, we assume the same relative reduction potential exists for these mechanical parts as for tires.

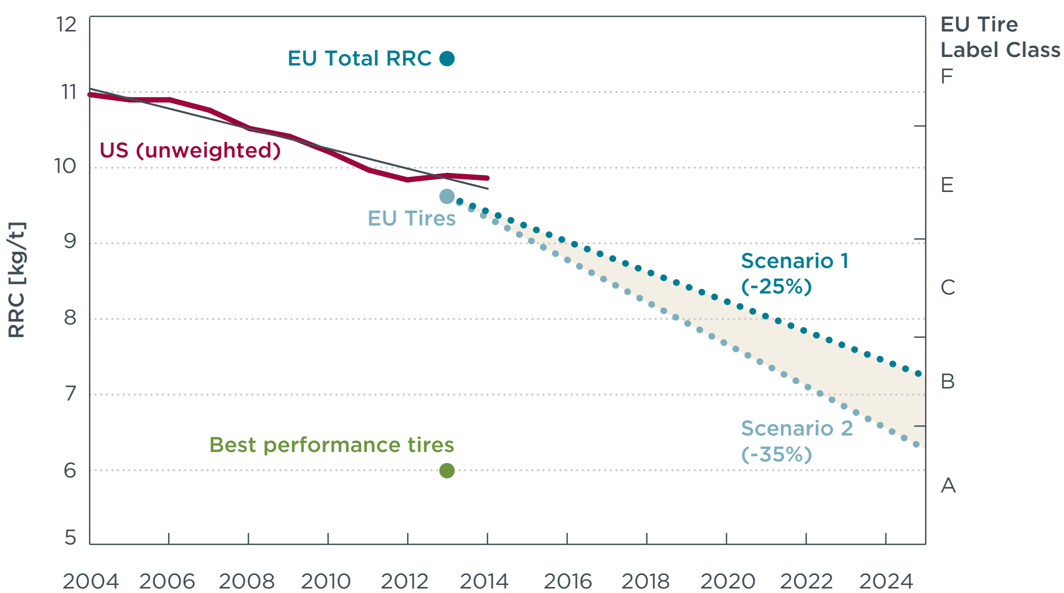

Figure 15. Rolling resistance: 10-year trend U.S. (total rolling resistance), status quo EU (total and tires only) and projections to 2025.

Figure 15 depicts the 10-year U.S. trend and two scenarios defined for the European market. The U.S. data here are not sales-weighted, and because of the increasing number of large and low-volume car models in the U.S. market during the past 10 years, the trend most likely underestimates the real sales-weighted fleet averages. Taking this shortcoming into account, the observed U.S. trend is already in good agreement with the more theoretical development of the EU development (scenario 1: -25% until 2015). The widespread deployment of best-performance tires would lead to the total scenario 2 reduction of 35%.

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4.3 AERODYNAMIC DRAG

Considering the statistical data, as described in Section 3.3, slight improvements are observable concerning the LDVs' aerodynamic drag coefficients. Vehicle bodies become more smooth and streamlined, and openings in the chassis, like wheel houses, get redesigned to fulfill the more stringent needs of low resistance air streaming. On the other hand, technical improvements are limited by physical boundaries, such as the minimum interior space, safety devices or the unique characteristic shape of a specific vehicle model increasing the value of brand recognition and contrasting with competitive models.

The total aerodynamic drag is influenced proportionally by the vehicle's frontal area, which is the projected area in the longitudinal direction. Therefore, increases in height and width have a direct negative impact on the aerodynamic forces. Regarding the total EU fleet average, a strong increase of the mean frontal area of EU passenger cars can be observed (see Figure 11 in Section 3.3). This is mainly due to shifts of sales numbers among the vehicle categories, especially due to the large growth of the small SUVs in the J segment. But also within the classic A to E vehicle segments, the frontal areas enlarged significantly during the past 10 years and almost completely offset the positive effects of aerodynamic improvements.

However, new car generations of the upper vehicle segments currently coming to market, like the VW Passat, the Mercedes C class, or the BMW 7 series, already do not show further increasing frontal areas any more, indicating that this adverse trend will be slowed or even stopped completely on a total fleet level within the next couple of years. The wider use of active suspension – a system of actuators to raise and lower the chassis independently at each wheel – enables the reduction of the frontal area at higher vehicle velocities and could support this development. Hence, future improvements of the vehicles' aerodynamic body and structure will directly affect the total aerodynamic drag. Technical potential for active and passive aerodynamic improvements can also be seen for specific exterior parts, such as active grill shutters or wheel case diffusers.

The km77 database (km77.com, n.d.) includes aerodynamic drag coefficients and frontal areas for about 10% of all vehicle models available in the European market. This is mainly a collection of data published by the manufacturers over the past decade. The provided data sets were grouped by the LDV segment classification, and averages and best-performing vehicle models were determined for each vehicle segment. The results of these analyses are summarized in Table 13.

Two scenarios were derived from the achieved results:

Scenario 1: Under this less ambitious scenario, the average technical potential over all relevant LDV categories was quantified by 14%, expressed as the difference between the vehicle model with lowest aerodynamic drag and the average of each vehicle segment. Taking into account small natural size differences between individual models even within the same segment, the average difference between the top-performer and all models of one segment regarding aerodynamic characteristics is close to 10%. It is assumed that this value represents the state-of-the-art construction knowledge achieving an optimized streamlined vehicle chassis that will be adapted by all manufacturers to all models until 2025.

Scenario 2: In this more ambitious scenario, the identified individual top performing car models are nearly 20% better than their respective segment average. The Opel Astra provides one example in the C segment. It is assumed that this improvement can be achieved on the overall fleet level only with high effort by applying the most sophisticated technologies on a broad basis.

Table 13. Aerodynamic drag – best available performing vehicle models of each vehicle segment (unadjusted data from km77 data base)

LDV segment	Average $C_d * A_f$ (m²)[11]	Model with lowest $C_d * A_f$ (m²)		lowest/average -1
A	0.68	VW Lupo	0.63	-8%
B	0.67	Nissan Micra, Seat Ibiza, VW Polo	0.61	-10%
C	0.70	Opel Astra	0.56	-19%
D	0.65	Mercedes C class	0.54	-16%
E	0.69	Mercedes E class	0.57	-17%
J	0.88	BMW X1	0.75	-15%
N1 III	1.25	Mercedes Vito	0.99	-21%
Average				**-14%**

In Figure 16 two different trend projections are included: "EU Trend fleet" describes the continuation of the current volume shift among different vehicle segments toward classes of larger vehicles, in particular SUVs, while "EU Trend segments" ignores this fleet internal shift, instead assuming constant segment market shares. Hence, this projection represents the current trend within the individual vehicle segments. Assuming rather constant shares of the segments, a realistic potential of around 10% reduction until 2025 was derived from trend data and plausible assumptions (scenario 1), with a further 10% reduction potential considering the top performing vehicles which are currently available on the market (scenario 2: -20%).

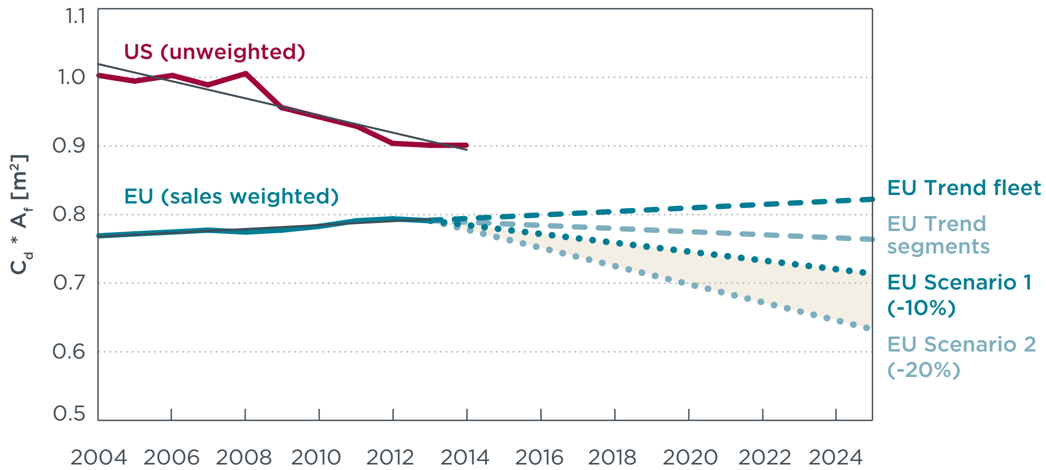

Figure 16. Aerodynamic drag: 10-year trends with U.S. and EU and projections to 2025.

11 Segment averaged aerodynamic drags in the table are related to available data sets from km77 and are not adjusted to realistic fleet averages. A general adjustment factor of 1.11 was derived from supplemental analyses, reflecting the fact that most data published by manufacturers are from vehicle models with outstanding performance, and so reflect only those versions of a model with the best aerodynamics.

4.4 SUMMARY OF SCENARIOS

The 10-year trend data for LDV masses, rolling resistances and aerodynamic drags have been collected and evaluated. From current European databases, the best-in-class vehicles with regard to mass and aerodynamic drag and the tires on the market with lowest rolling resistance were identified. Based on these evaluations, two scenarios for the 2025 time horizon were developed. The first scenario reflects the current average deviations between best-in-class technologies and standard application technologies. The second scenario, on a more ambitious level, is based on the currently observed top performing technologies, reflecting the maximum achievable technical improvements until the reference year 2025. For scenario 1 reduction rates of 10% were derived for mass and aerodynamic drag, along with a 25% reduction rate for rolling resistance. For scenario 2, the maximum feasibility was quantified by 20% for mass and aerodynamic drag and by 35% for the RRC. The results about the current 10-year trend and the assumed reduction rates for the two scenarios are summarized in Table 14.

Table 14. Driving resistances of new LDVs on the EU market – 10-year trend and scenarios for 2025

	Trend (10 years) annually	Scenario 1 2025	Scenario 2 2025
Mass	+0.4%	-10%	-20%
RRC	-1.3% *	-25%	-35%
Aero drag	-0.3%	-10%	-20%

** Based on U.S. data, which do not reflect EU legislation.*

Even the scenario 1 predictions exceed the real trends currently observable in the markets. It is assumed implicitly that the tightened CO_2 emission standards in the EU will have a clear impact on manufacturers' decisions to apply fuel- and CO_2-saving technologies to a much greater extent than is the case today. This study indicates that rolling resistance has the highest relative reduction potential, because technology is already available and relatively easy to apply. Mass reductions are technically feasible, but require more effort and might become less attractive with sophisticated recuperation systems. Measures to reduce aerodynamic drag offer medium potential and are limited by physical boundaries and potential technical conflicts.

5. CONCLUSIONS

The driving resistances of a moving vehicle are the main influencing parameters for its fuel consumption and CO_2 emission performance. Optimizations of the relevant physical parameters are of high importance in improving emission behavior. Ten-year trends and technically possible 2025 scenarios for the relevant parameters were determined in this study. The results are based on comprehensive European data sources. For purposes of comparison, some results from U.S. data evaluations also were considered, revealing similar characteristics but also showing regional differences for some of the parameters examined.

The 2025 scenario predictions on driving resistances in this study exceed the real trends that are currently observable on the markets. It is assumed implicitly that the tightened CO_2 emission standards in the EU will have a clear impact on manufacturers' decisions to apply fuel- and CO_2-saving technologies to a much greater extent than is the case today.

Mass

Detailed and reliable sales-weighted data for the EU market were available and have been evaluated. The 10-year trend shows mass increasing significantly, although slightly. An annual addition of 0.4% in relation to the car fleet average can be observed, which is in good agreement with the 10-year U.S. development where 0.6% unweighted increases and 0.3% sales-weighted increases per year could be derived. This slightly increasing trend can be observed consistently for all car segments except for SUVs, where the EU market has clearly shifted to a larger number of smaller and lighter versions. The statistical evaluations show that mass has been a rather stagnant parameter with slow changes over time, being coupled with the vehicle generations' life times. However, for most segments the mass curve has flattened over the past 3–4 years; some manufacturers have already achieved substantial reductions for new model generations; and the total extent of technical capabilities are demonstrated in some selected market models. Reflecting the results of best-in-class analyses, technical scenarios of 10% and 20% mass reduction were derived for 2025.

Concerning future electrified propulsion concepts, mass might not be the most attractive driving resistance parameter for reductions, because sophisticated recuperation systems can compensate for a large portion of the energy consumed during vehicle accelerations. On the other hand, other positive impacts of mass reduction, such as better acceleration performance, also will provide substantial consumer value.

Rolling resistance

The situation of rolling resistance is different compared to the other load parameters as innovative tires are already on the market and their deployment is much more under the control of the tire manufacturers and vehicle owners, rather than being determined by vehicle manufacturers' long-term investment decisions. Technically, mitigation of driving resistance can be achieved relatively quickly, with low effort and at relatively low cost levels. Reduction of rolling resistance is much more up to policy decisions and tradeoffs with ride, handling, and cost.

The European situation until 2025 will be determined mainly by three regulatory measures:

1. The prohibition of tires with high RRCs will strongly shift the RRC distribution of the EU market tires to mainly C labeled tires, involving an annual RRC reduction of -1.9% until 2019. G labeled tires already are banned from series vehicles, and F labeled tires will follow in September 2018.
2. The introduction of the EU tire labeling system provides information about the RRC and will increase consumer demand for very effective tires. Experts expect 75% market shares of A and B labeled tires in 2025, which corresponds to an annual average RRC reduction of -2.1%.
3. The introduction of the WLTP as the regular type-approval procedure for LDV, currently planned for 2017, under which the certified CO_2 and fuel consumption values for individual vehicle performance will directly reflect the effect of the mounted tires.

Useful for comparison, the unweighted mean 10-year U.S. trend for rolling resistances was quantified by -1.3% per year, and likely would be slightly larger if sales-weighted data were used. The European regulatory measures will lead to an accelerated and even more dynamic positive development. The current distribution of tire RRC in the EU market was analyzed, and the influence of the legal measures on future average and scatter range was projected. Two scenarios were established for 2025, resulting in 25% and 35% reductions in rolling resistance.

Aerodynamic drag

The EU databases for the most relevant vehicle segments consistently show rather small changes over the past 10 years. Only the J segment features clear improvements, but this is mainly because of the intensified demand for smaller SUVs; overall, that shift degrades the aerodynamic drag balance for the total car fleet. Improvements in aerodynamics for segments A to D are observable on the order of 0.5% per year, but are almost fully offset by increased frontal areas. These results of neutral developments are in good agreement with the U.S. trend derived from the EPA official test database.

Improvements in aerodynamics are technically demanding and very often are linked with other functional negative impacts such as driving comfort reductions, reduced space, or unwanted changes in the vehicle's design. Thus, intentions to making the vehicle body more streamlined often are in conflict with other development targets. However, the growth of frontal areas within the specified segments probably will be slowed, or even completely stopped, within the next couple of years. The widespread introduction of active suspension systems that result in reduced frontal area at higher vehicle velocities could support this development. Hence, future improvements of the vehicles' aerodynamic body and structure will directly affect the total aerodynamic drag. Regarding improvements of the aerodynamics, technical potential can be seen for specific exterior parts, such as active grill shutters or wheel case diffusers. Reflecting the results of best-in-class analyses, the total technical potential was determined to be a 10% reduction for the first scenario and 20% for the second scenario.

CO_2 emission reduction potential

Combining the predicted reductions of the driving resistances, shown in Table 14, with the CO_2 sensitivities in Table 3 results in the total CO_2 emission reduction potential that can be achieved by load reductions, as summarized in Table 15. Again, two scenarios were developed, indicating a plausible range of technical feasibility for each parameter.

Table 15. CO_2 reduction potential due to improved driving resistances for the EU LDV fleet average (based on the WLTC driving cycle)*

	Current trend (per year)	Scenarios		CO_2 %/10% red.	CO_2 reduction 2025	
		1	2		1	2
Mass	**+0.4%**	-10%	-20%	-7%	-7%	-14%
Rolling Resistance	**-1.3%**	-25%	-35%	-1.5%	-4%	-5%
Aerodynamic Drag	**-0.3%**	-10%	-20%	-3%	-3%	-6%
Total CO_2 saving potential					**-14%**	**-25%**

** including assumed secondary mass effects and adjusted engine performance*

The total CO_2 reduction potential in 2025 regarding the technical feasibility of individual vehicle models was quantified between 14%, for scenario 1, and 25%, for scenario 2. All three types of driving resistance parameters contribute by rather similar amounts, although mass reduction will likely give the highest benefit of the three resistance parameters. The CO_2 sensitivity of rolling resistance is comparatively low, but available low rolling resistance tires are clearly exceeding the current market averages. These are easy to introduce, especially when accompanied by legal regulatory measures. Improvements in aerodynamic drag are also promising, especially if the ongoing trend of enlarged frontal areas can be stopped, and the improvements in further streamlining the vehicle body can be fully transformed into CO_2 savings.

Some uncertainties remain regarding electrified propulsion systems, where the current model approaches still have not reached the same level of accuracy as for the conventional vehicles propelled only by combustion engines. For electrical hybrid vehicles, the share of pure electric driving still has to be better assessed, and new technical features, such as high efficiency recuperation systems that reduce the losses during acceleration, still need to be better implemented in vehicle emission models.

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APPENDIX A: MASS – TRENDS BY VEHICLE SEGMENTS

All segment specific mass averages in this appendix are sales-weighted data for the EU and unweighted data for the U.S. EU values are mass in running order; U.S. values are the test mass. Ten-year averages shown are per annum (p.a.).

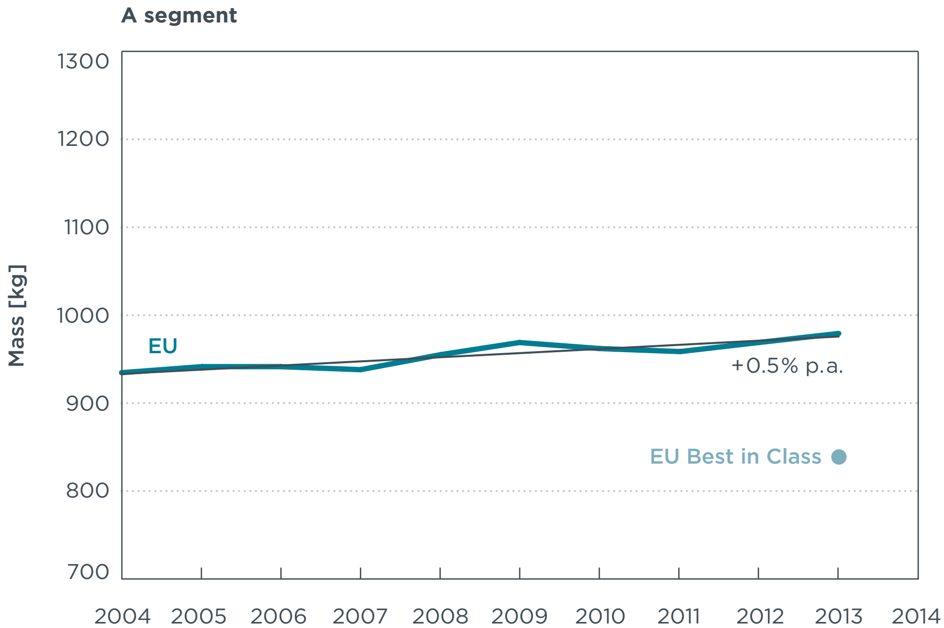

Figure A-1. Vehicle mass of A segment cars in the EU – Annual averages of the past 10 years and actual best-in-class model.

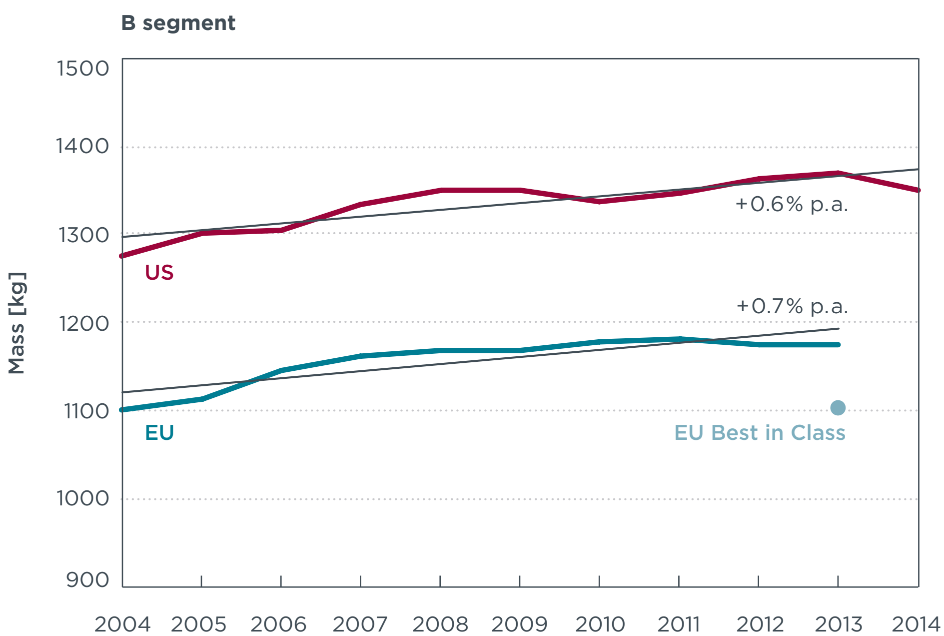

Figure A-2. Vehicle mass of B segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

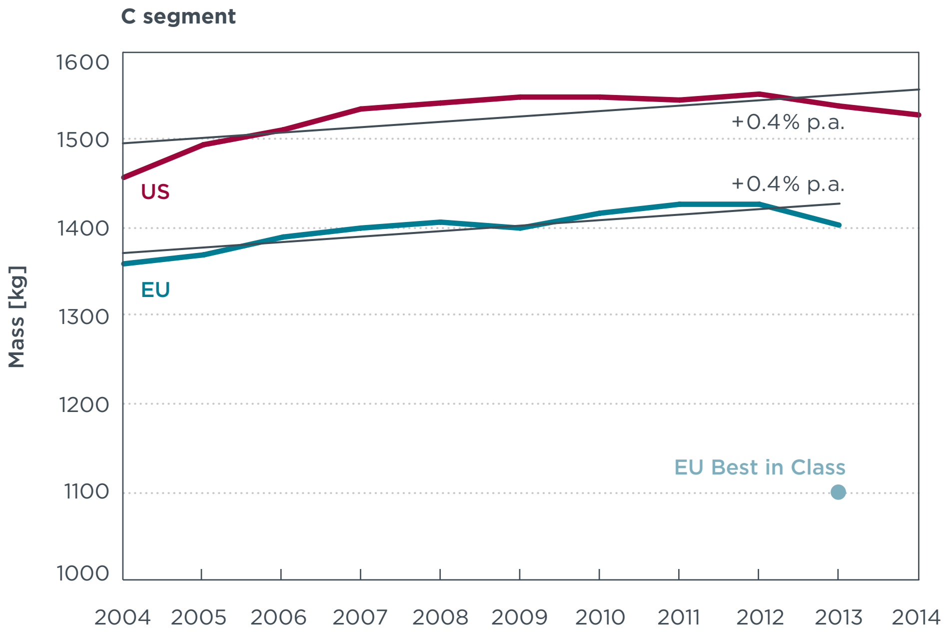

Figure A-3. Vehicle mass of C segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

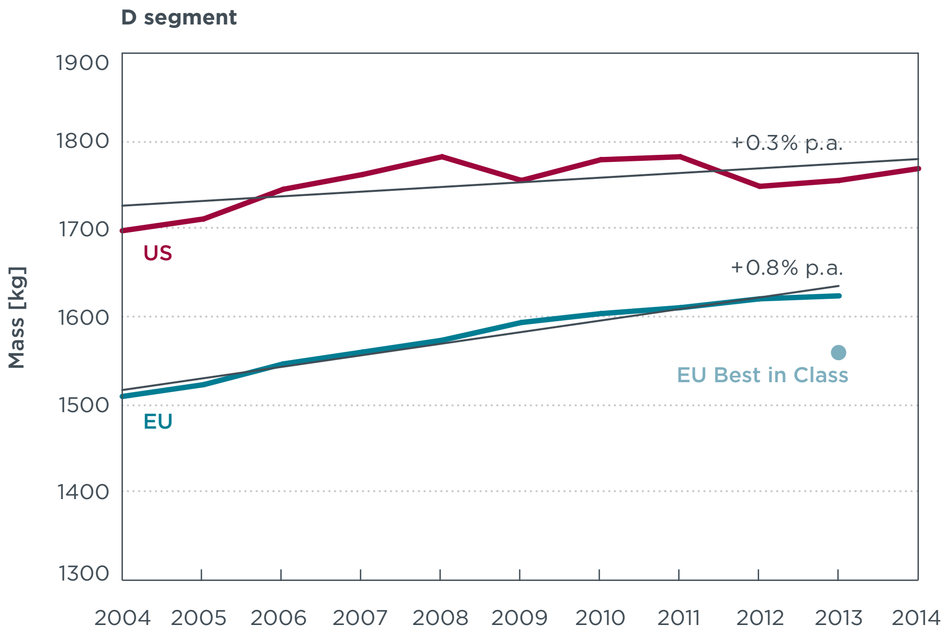

Figure A-4. Vehicle mass of D segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

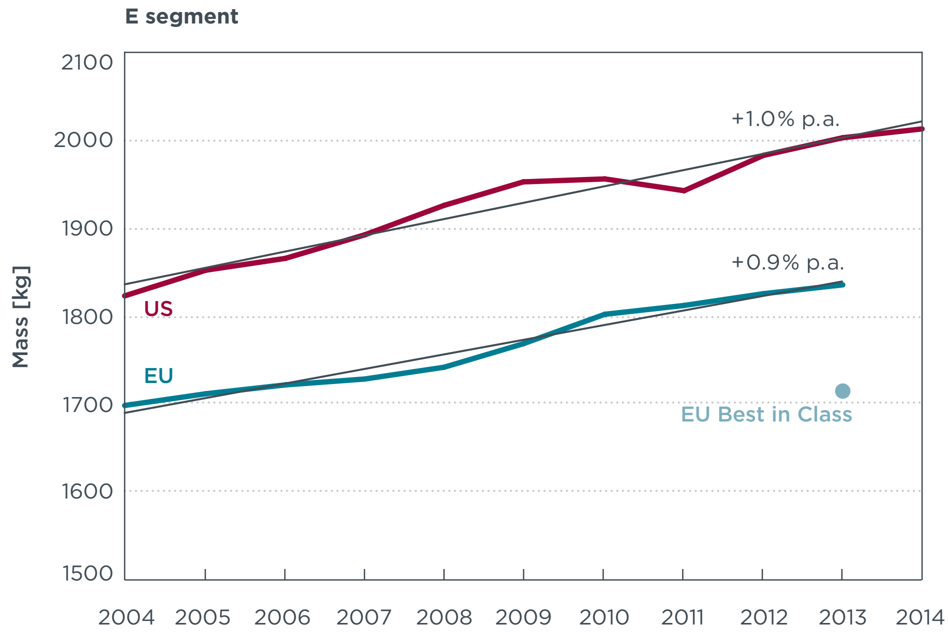

Figure A-5. Vehicle mass of E segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

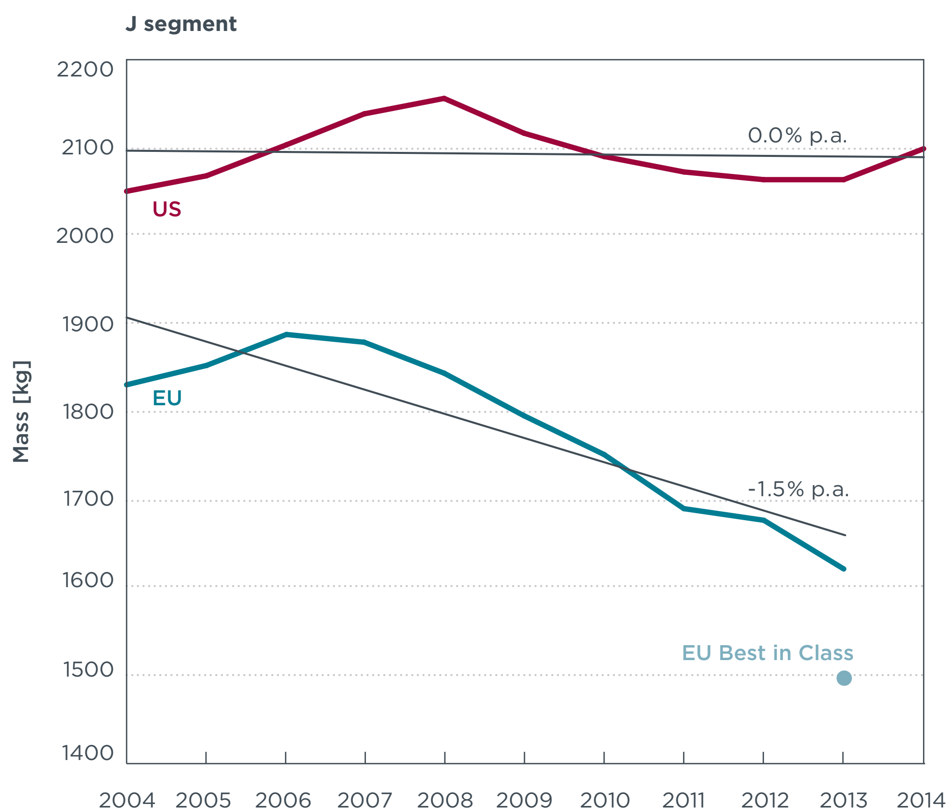

Figure A-6. Vehicle mass of J segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

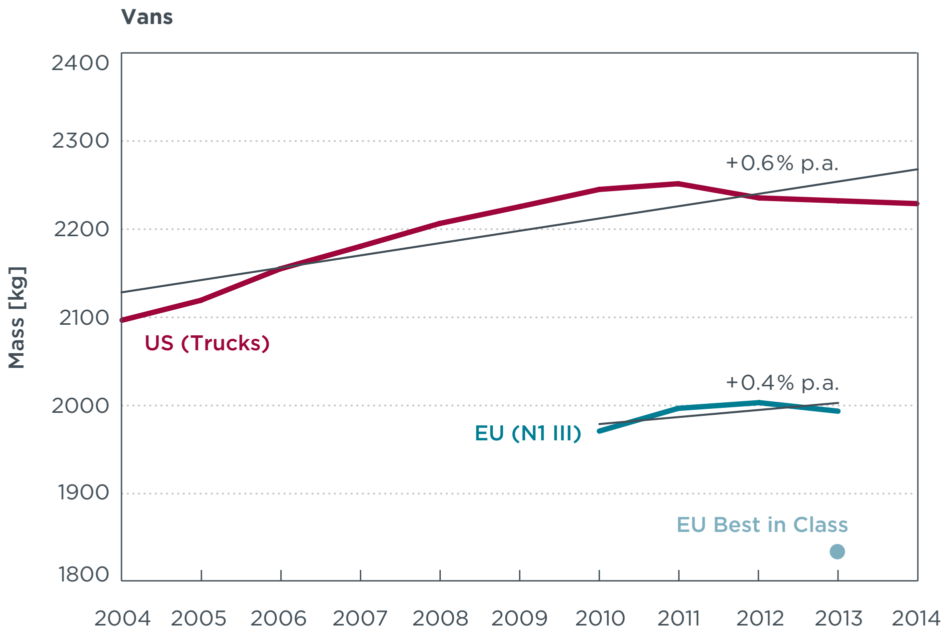

Figure A-7. Vehicle mass of vans in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

APPENDIX B: ROLLING RESISTANCE – TRENDS BY VEHICLE SEGMENTS

All segment-specific RRC averages in this appendix are sales-weighted data for the EU and unweighted data for the U.S. Ten-year averages shown are per annum (p.a.).

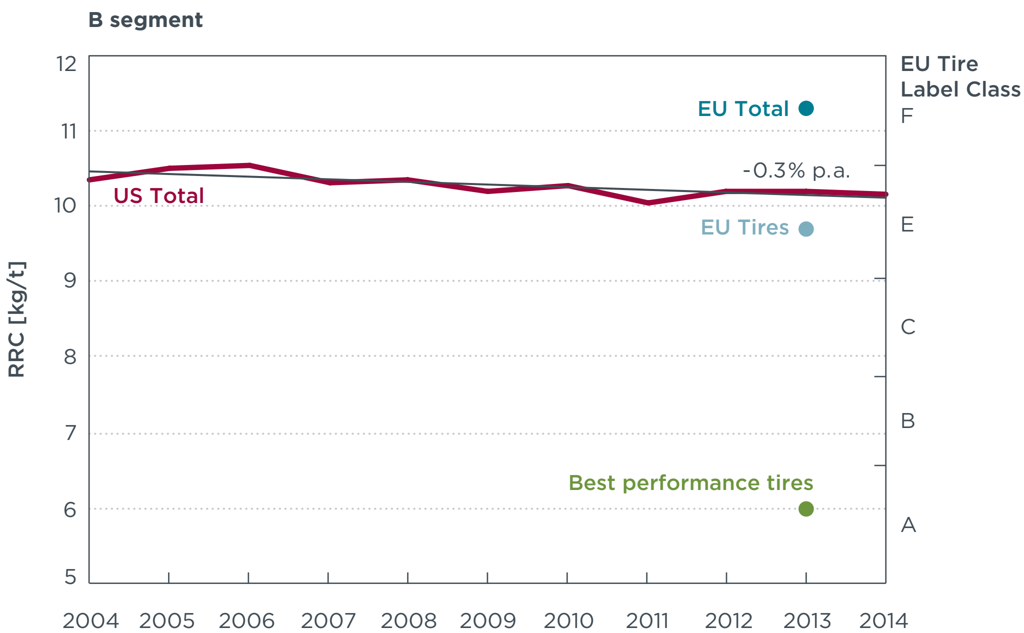

Figure B-1. Vehicle rolling resistance of B segment cars – Annual averages of the past 10 years in the U.S. and actual EU averages (total vehicle and tires only).

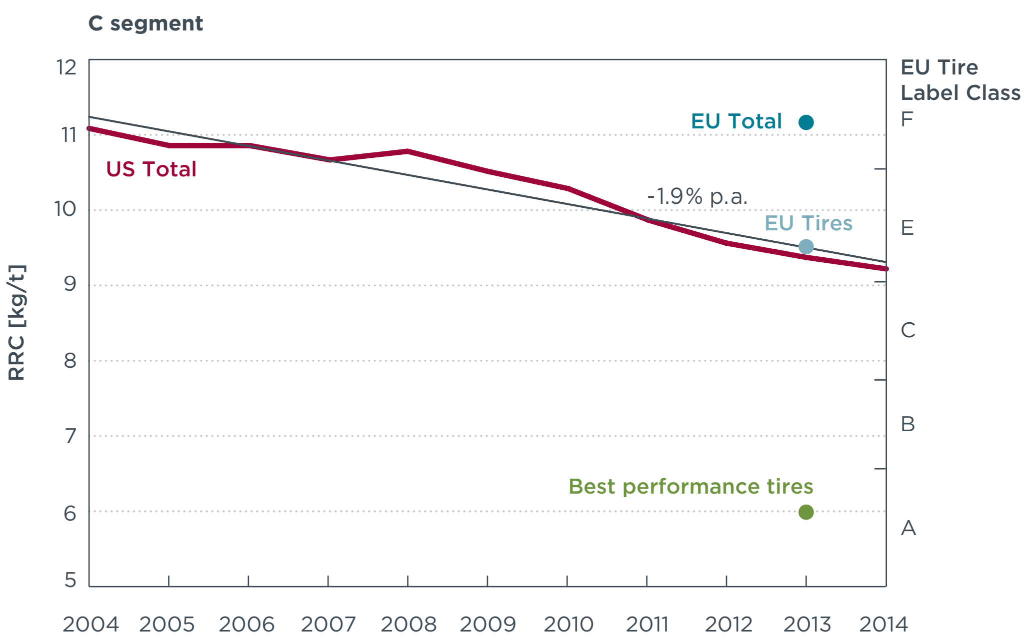

Figure B-2. Vehicle rolling resistance of C segment cars – Annual averages of the past 10 years in the U.S. and actual EU averages (total vehicle and tires only).

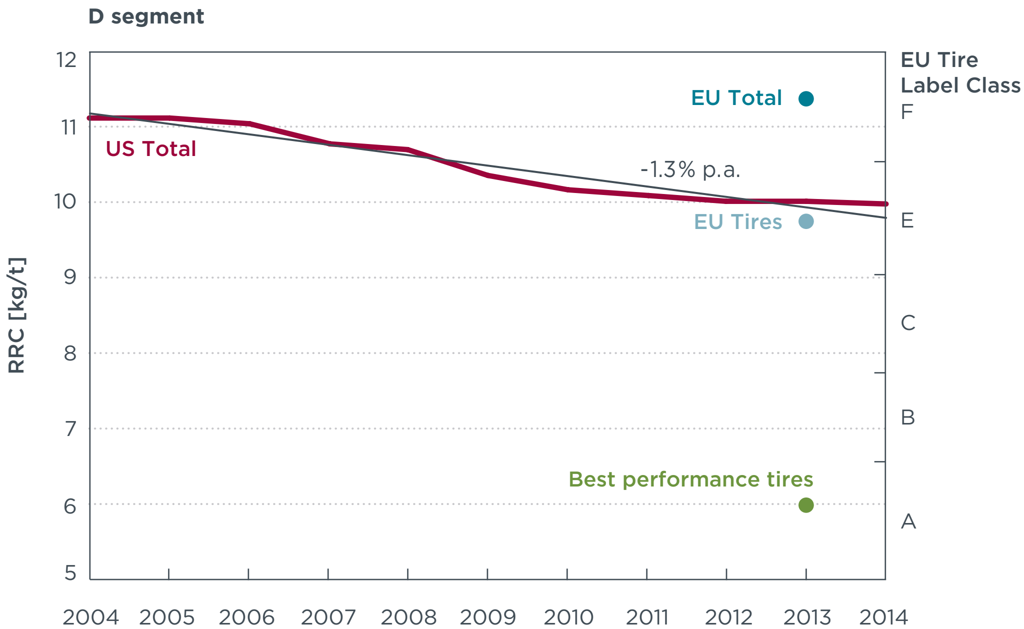

Figure B-3. Vehicle rolling resistance of D segment cars – Annual averages of the past 10 years in the U.S. and actual EU averages (total vehicle and tires only).

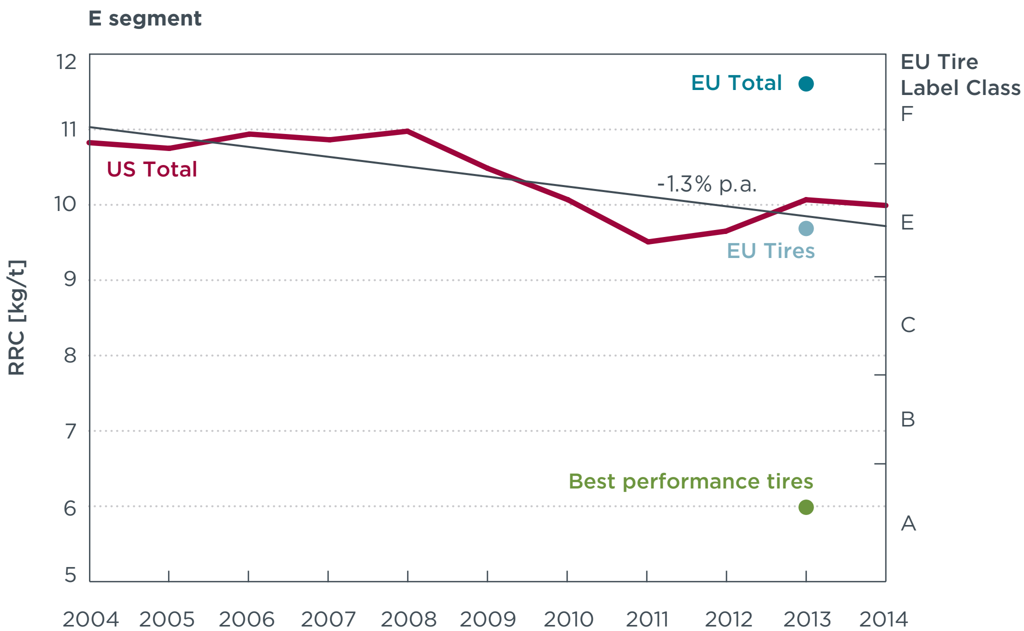

Figure B-4. Vehicle rolling resistance of E segment cars – Annual averages of the past 10 years in the U.S. and actual EU averages (total vehicle and tires only).

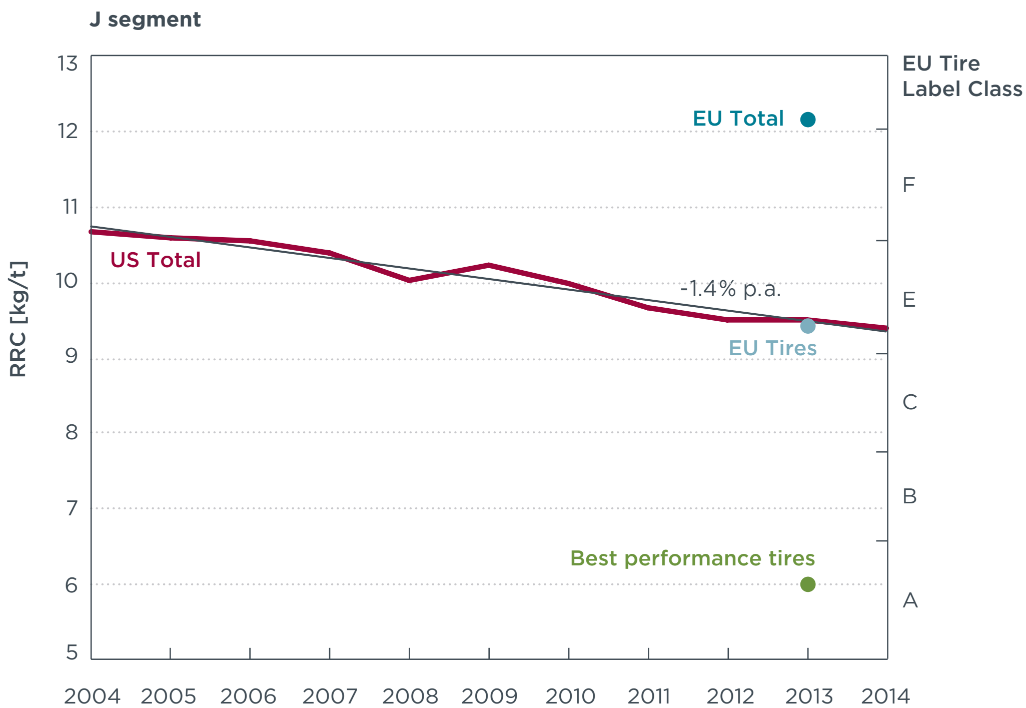

Figure B-5. Vehicle rolling resistance of J segment cars – Annual averages of the past 10 years in the U.S. and actual EU averages (total vehicle and tires only).

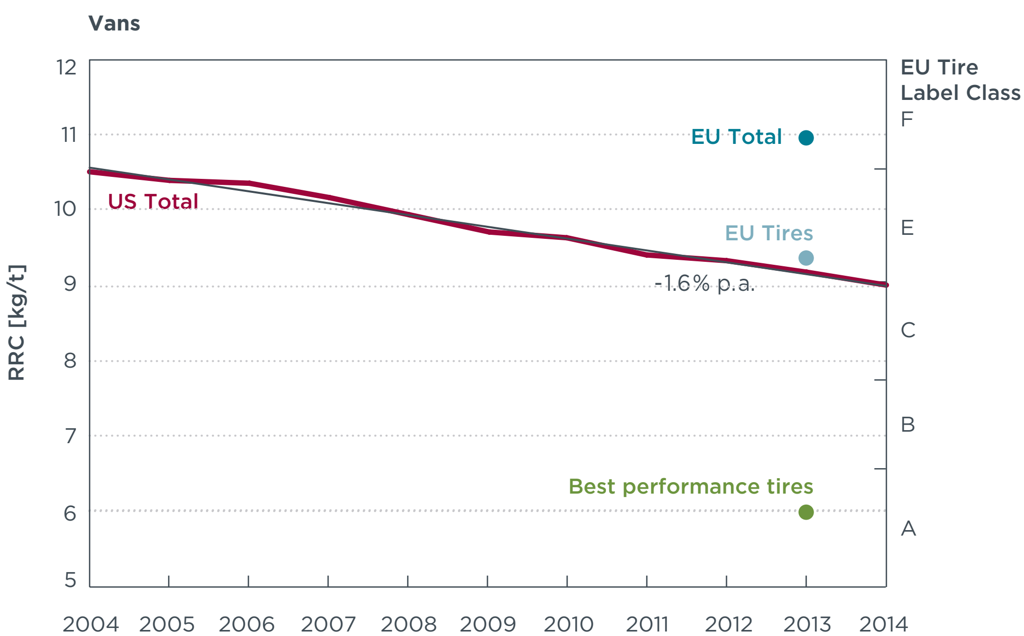

Figure B-6. Vehicle rolling resistance of vans Annual averages of the past 10 years in the U.S. and actual EU averages (total vehicle and tires only).

APPENDIX C: AERODYNAMIC DRAG – TRENDS BY VEHICLE SEGMENTS

All segment-specific aerodynamic drag averages in this appendix are sales-weighted data for the EU and unweighted data for the U.S. Ten-year averages shown are per annum (p.a.).

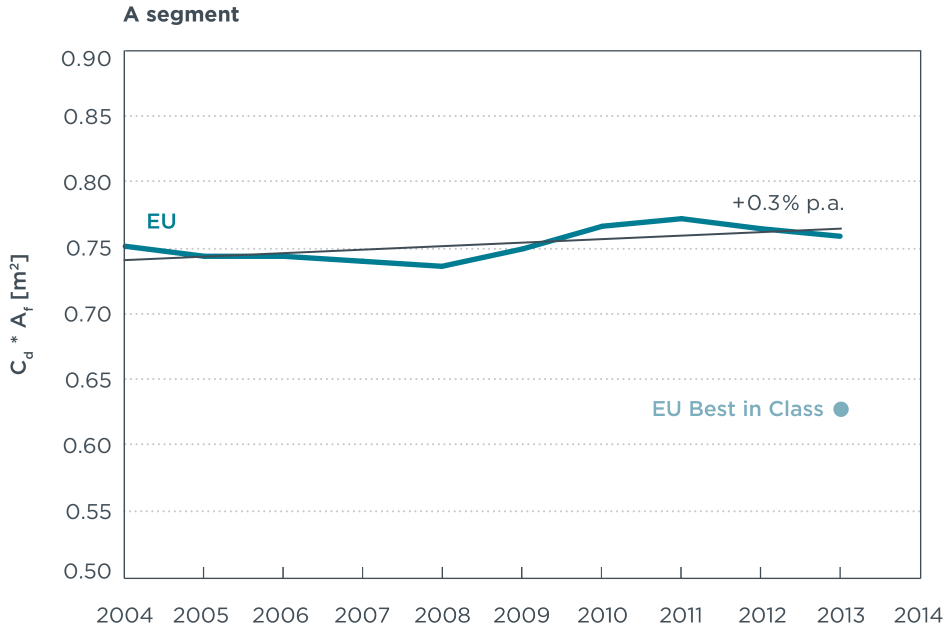

Figure C-1. Aerodynamic drag of A segment cars in the EU – Annual averages of the past 10 years and actual best-in-class model.

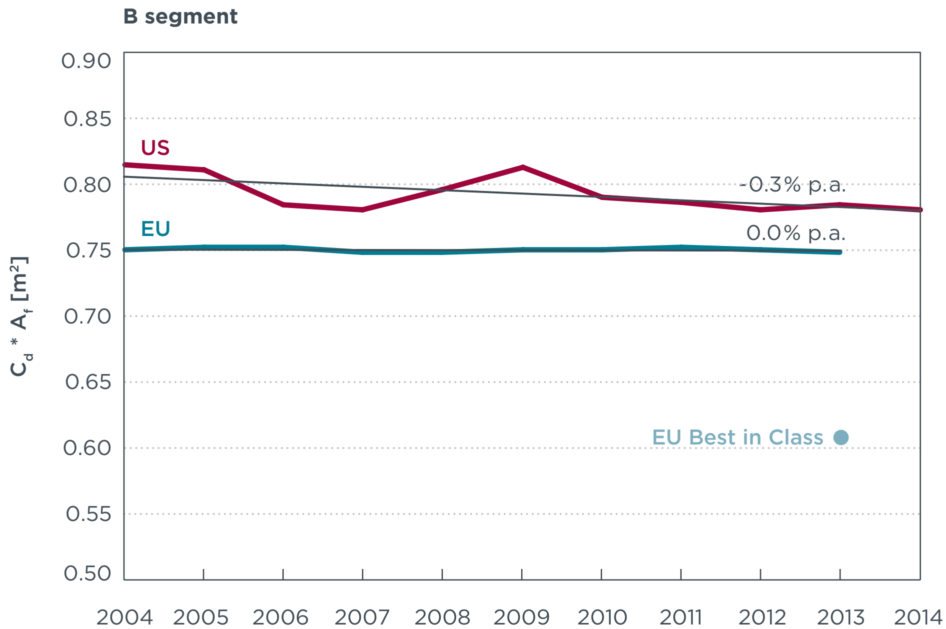

Figure C-2. Aerodynamic drag of B segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

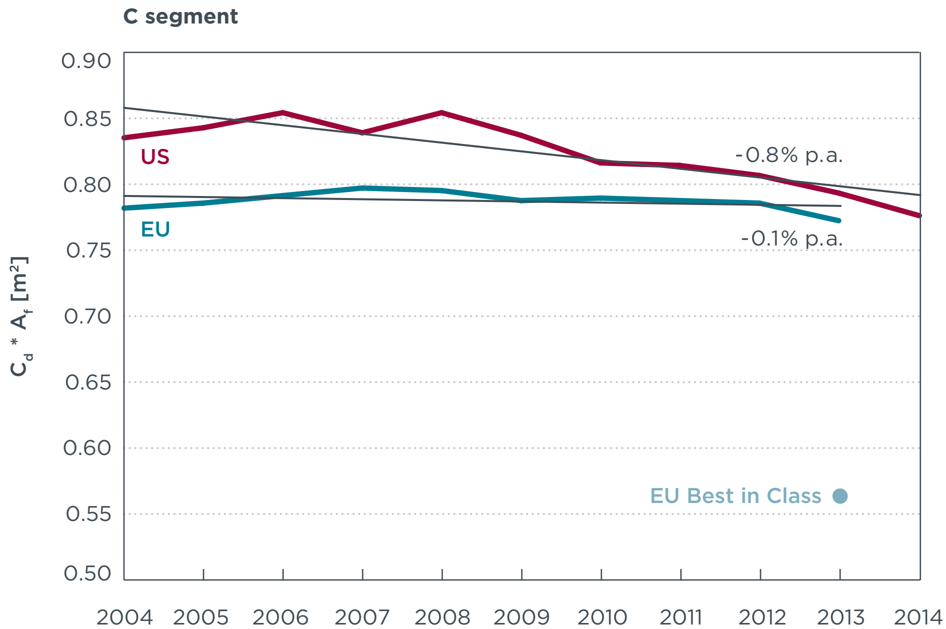

Figure C-3. Aerodynamic drag of C segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

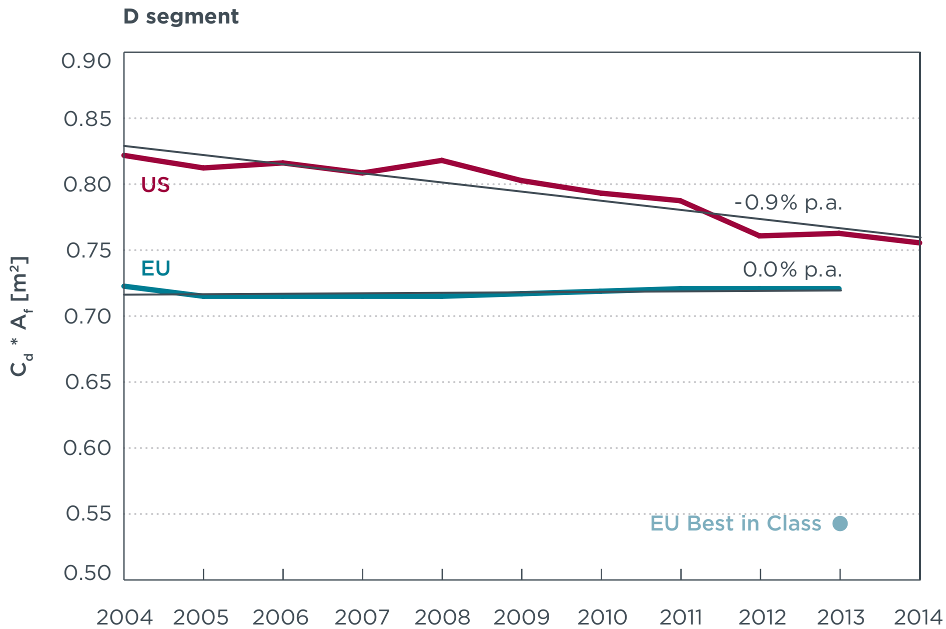

Figure C-4. Aerodynamic drag of D segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

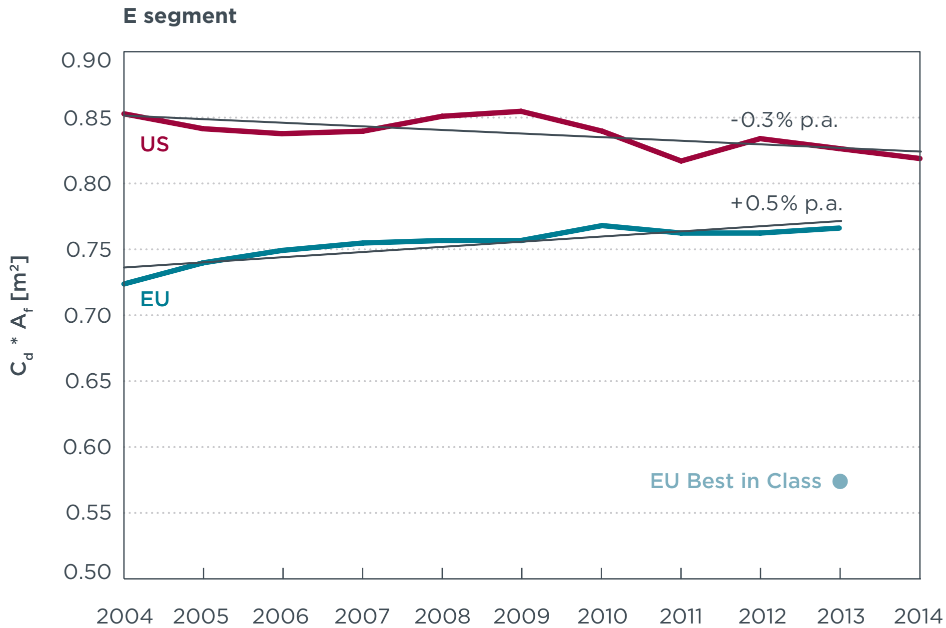

Figure C-5. Aerodynamic drag of E segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

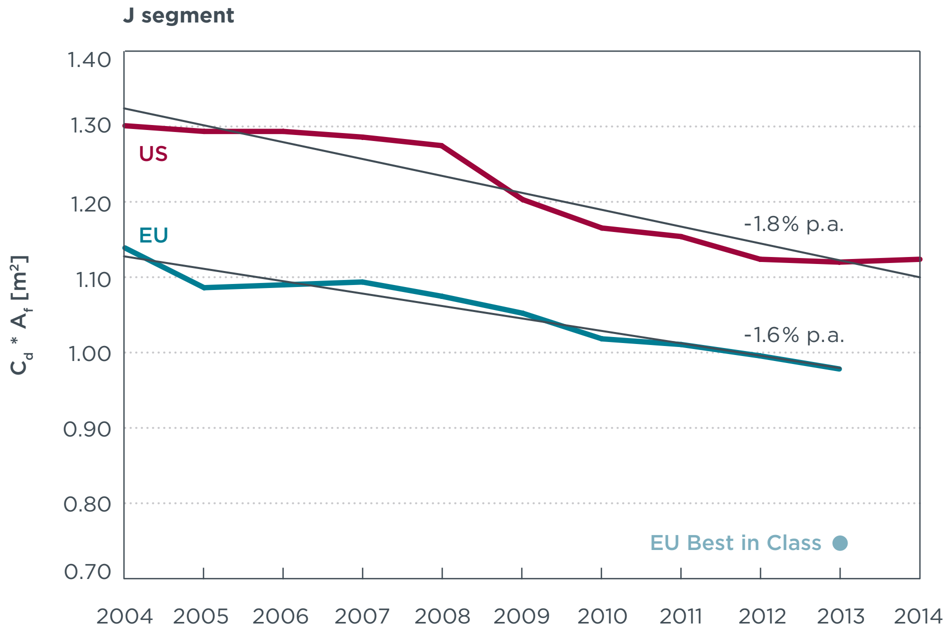

Figure C-6. Aerodynamic drag of J segment cars in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

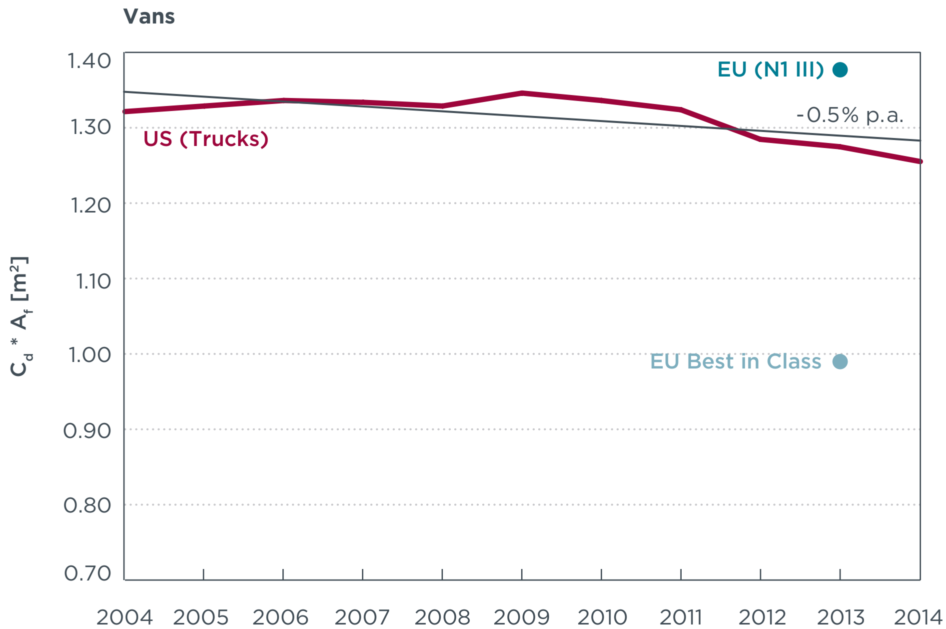

Figure C-7. Aerodynamic drag of vans in the EU and U.S. – Annual averages of the past 10 years and actual best-in-class model.

APPENDIX D: AVERAGE MAXIMUM VEHICLE LOADS AND WLTP TEST MASSES IN EU 2013

The WLTP foresees testing for a low load and a high load vehicle version within each vehicle family. In terms of mass, this means that the lower boundary is a "test mass low" (TML) vehicle version without any extras. The maximum extra equipment will be on board of the "test mass high" (TMH) version. Both TML and TMH versions also include 15% (N1 III: 28%) of the maximum permissible payload.

Table D-1. Masses of extra equipment, maximum payloads and resulting WLTP test masses

Segment	Maximum extras (kg)	Average extras (kg)	Maximum vehicle payload (kg)			WLTP test mass (kg)		
			TML	mean	TMH	TML	mean	TMH
Diesel								
B	150	60	410	350	260	1310	1361	1437
C	175	70	476	406	301	1530	1590	1679
D	225	90	476	386	251	1721	1797	1912
E	275	110	485	375	210	1935	2029	2169
J	275	110	482	372	207	1785	1879	2019
N1 III	220	88	749	661	529	2261	2324	2419
Gasoline								
B	150	60	390	330	240	1233	1284	1361
C	175	70	464	394	289	1440	1499	1588
D	225	90	454	364	229	1671	1747	1862
E	275	110	463	353	188	1894	1988	2128
J	275	110	430	320	155	1505	1598	1739