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Evaluation of fuel efficiency improvements in the Heavy-Duty Vehicle (HDV) sector from improved trailer and tire designs by application of a new test procedure

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Evaluation of fuel efficiency improvements in the Heavy-Duty Vehicle (HDV) sector from improved trailer and tire designs by application of a new test procedure

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1. EXECUTIVE SUMMARY

The International Council on Clean Transportation (ICCT) and Verband der Automobilindustrie (VDA) commissioned the Institute for Internal Combustion Engines and Thermodynamics of the Graz University of Technology (TU Graz) to carry out tests of fuel efficiency improvements in the heavy-duty vehicle (HDV) sector from improved trailer and tire designs by application of a new test procedure developed for the European Commission Directorate-General for Climate Action (DG CLIMA).

Physical testing of vehicles on a closed track is a useful method for measuring drag forces resulting from air resistance and adhesion between the tires and the road surface. Two methods of assessing total drag were implemented: coast down testing and constant speed testing. In coast down testing, the vehicle is accelerated to a certain speed and then allowed to coast to a stop or a designated lower speed. Evaluation of the recorded speed and distance data during the coast down yields the total drag force, which is then allocated to aerodynamics and rolling resistance based on standardized mathematical equations. In constant speed testing, the total drag is calculated using measured fuel consumption, engine data, and assumptions about the power demand from the auxiliaries and losses in the driveline while the vehicle maintains a constant speed.

The primary goals of this project were as follows:

1. Evaluate two methods for quantifying the differences in aerodynamic drag and rolling resistance.
   - Analyze the repeatability of both coast down and constant speed testing for the purpose of calculating aerodynamic drag and rolling resistance coefficients for fuel efficiency simulation modeling
   - Assess the sensitivity of the test results based on the aerodynamic features of the tractor and semi-trailer

2. Determine the fuel and greenhouse gas (GHG) reduction potential of improved technologies.
   - Aerodynamically optimized trailers
   - Low rolling resistance tires

To our knowledge, this project was the first time that coast down and constant speed tests with truck/trailer combinations were performed to investigate the repeatability and reproducibility of the two different test methods for determining the parameters "tire rolling resistance" and "air drag resistance". The tractors were provided by Daimler, and the trailers were provided by Krone and Schmitz Cargobull. The tests were performed on the Dekra test track in Klettwitz, Germany. Over three weeks an extensive measurement campaign was undertaken to derive driving resistances for four different trailers that were combined with two different versions of tires and two different settings of roof and side fairings on the tractor. Both constant speed and coast down tests were performed on the Krone standard and optimized trailers, and the results showed a slightly better repeatability for the constant speed tests than for the coast down measurements. With the fuel flow based constant speed tests the 95% confidence interval of the resulting aerodynamic drag was between 2% and 3.5% based on two test series of constant speeds. The 95% confidence interval of the results from the coast down tests was between 3.8% and 4.1% with three test series analyzed. The Schmitz optimized trailer was coast down tested; however, constant speeds were unable to be performed for comparison purposes. The 95% confidence interval of the coast down results for the Schmitz optimized trailer was 19%. The results show that the present development status of both test procedures for HDV cannot be the final version for the evaluation of these parameters.

A main uncertainty in the constant speed tests is seen in the actual method to determine the power demand at the wheel to overcome the driving resistances. This power is computed by data from the engine fuel flow measurement, which is used to interpolate the actual engine power from the engine fuel map. Then the power demand from auxiliaries and losses in the drivetrain are subtracted. To improve the accuracy it is necessary to measure the torque directly at the rim in future. This suggestion is already considered for a pilot phase of the DG CLIMA test procedure in 2012.

For the tested Krone trailers the reduction in air resistance for the optimized trailer as compared to the standard trailer was measured to be 4% from the constant speed and 9% from the coast down tests. The relatively small differences in aerodynamic drag measured in the constant speed tests highlight the importance of a robust and sensitive test method.

The relative differences between the trailers did not show a significant dependency on the design of the tractor as long as the trailer variations were measured with the same tractor setup. The methods applied for the determination of the aerodynamic drag do not cover the influence of cross-wind conditions. The importance of this influence in the comparison of the real world performance of different trailers has to be further investigated. During most of the testing there were no cross-winds, and thus these tests do not provide data for a sound analysis of the effects of the aerodynamic technologies during cross-wind conditions.

During vehicle testing, use of tires with lower rolling resistance on the trailer only (not on the tractor) reduced the rolling resistance of the entire truck-trailer combination by 23%. The tests on a drum according to ISO 28580 performed at the test stands of the tire manufacturers showed a reduction in tire rolling resistance (RRC) of 18%. This difference is within the accuracy of the constant speed tests at low vehicle velocities in the setup applied here and due to driving resistances that were not considered (e.g. bearing friction and residual braking forces). Thus the results suggest that the RRC values from the drum tests can be used in a future CO_2 test procedure for HDV. However, due to the limited number of vehicles tested, no generalized valid conclusions can be made.

The influence on fuel consumption was simulated by the Passenger car and Heavy duty Emission Model (PHEM) using:

- measured values for air resistance
- vehicle weights
- RRC values calculated from the drum test values and the axle loads
- fuel map of the engine
- estimates of losses in the transmission and the power demand of the auxiliaries

This approach reflects the test procedure suggested for a future European regulation, which uses component testing in combination with a simulation tool for modeling the entire HDV.

Using the standard tractor in combination with an average laden standard trailer (payload = 19,300 kg) and high RRC tires as baseline, low RRC tires provide approximately a 4.5% reduction in fuel consumption per ton-km in typical long haulage driving cycles. Combined, low RRC tires and aerodynamic features on the trailer (in combination with a reduction of the trailer weight of 500kg) were shown to reduce fuel consumption by 6.5%. Furthermore, when the weight of the trailer was additionally reduced by 800 kg this resulted in an 8% total (i.e. the combined effects of aerodynamic features, low RRC tires, and reduced trailer weight) fuel consumption benefit.

1 INTRODUCTION

The Directorate-General for Climate Action (DG CLIMA) has commissioned a project[1] to develop a test procedure for measuring fuel use and greenhouse gas emissions from heavy-duty vehicles. The test protocol shall allow for the assessment of fuel consumption and CO_2 emissions of the entire truck and trailer combination by testing single components to obtain input data for a standardized simulation tool. In this test procedure basic tests for each truck and tractor model shall be performed with a standardized trailer or with a standardized body of the vehicle. To provide incentive for improving the design of trailers and bodies, it is envisioned that manufacturers will be given the option to test alternative trailers and bodies versus the standard trailers and bodies. From these tests the differences in driving resistances and weight can be obtained, and this data can be input into a standardized computer simulation tool. The tool simulates the complete vehicle over a standardized drive cycle(s) and then delivers the fuel consumption and CO_2 emissions results of the alternative vehicle set up. The modular approach of the test procedure allows also allocating the fuel savings to tires, aerodynamic drag, weight and losses in the drivetrain (Rexeis, 2011).

The theoretical background for this procedure has been elaborated already. Basically, the differences in air resistance will be measured either by constant speed driving or with coast down tests. The option that is more suitable for testing the differences between the standard and alternative trailers has not been determined in the DG CLIMA project.

This project aimed to improve the knowledge on the advantages and disadvantages of the potential test methods as well as on possible future improvements to increase the accuracy and the cost efficiency of the test procedure. For these tasks measurements on a test track with two tractors and four different trailers using different tires and also different configurations of roof fairings and different loadings of the trailers have been performed. The measured data was analyzed to test the repeatability of the test method and to obtain the influence of the design characteristics on the aerodynamic drag. Using the measured data, the effect on the fuel consumption of the articulated truck was simulated for typical driving conditions.

2. METHODOLOGY

The tractor-trailer combinations were measured on a test track[2] suitable both for coast down tests and for constant speed tests of Heavy Duty Vehicles (HDV). The tractors and the trailers as well as the test matrix are described in the following section.

2.1. Tested tractors

For the tests two identical Mercedes Actros 1848 with fully automated 12-speed gearboxes were provided by Daimler AG Stuttgart. The fitted engine was a Mercedes-Benz OM501LA engine fulfilling the emission standard EURO V. The engine is a V6 direct injection diesel, turbo-intercooled with a cubic capacity of 12 liters equipped with a SCR exhaust gas after-treatment system. The aerodynamic features like roof fairings and baffles were the same on both trucks. **Table 1** shows the technical specifications of the tractors.

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[1] "Reduction and testing of Greenhouse Gas Emissions from Heavy Duty Vehicles – LOT 2"

[2] Dekra test track in Klettwitz

Table 1: Technical Data Mercedes Actros 1848

Mercedes Actros 1848	
Engine typ	Mercedes Benc OM 501 LA V6 direct injection diesel 4 valves per cylinder turbo intercooled
Cubic capacity	11.95 litres
Max. power	350 kW / 1800 rpm
Max torque	2100 Nm / 1080 rpm
Exhaust gas after treatment	SCR catalytic converter
Tyres front axle	Continental HSL1 Ecoplus
Tyres rear axle	Continental HDL1 Ecoplus
Total weight	6900 kg

2.2. Tested trailers

The trailers were provided by Krone and Schmitz Cargobull. Both manufactures supplied one standard trailer for a 40 ton GVW tractor-trailer combination and one aerodynamically optimized trailer. The Krone standard trailer and the optimized trailer were 3-axle trailers with side curtains. The optimized Krone trailer used a stronger side curtain and wheel covers to minimize the air resistance (**Figure 1**).

The standard tire type at both Krone trailers was the Michelin X Energy Saver Green (low rolling resistance tires, fuel saving tires). For one test setup the standard trailer was equipped with Michelin Regio tires (standard tires with higher rolling resistance).

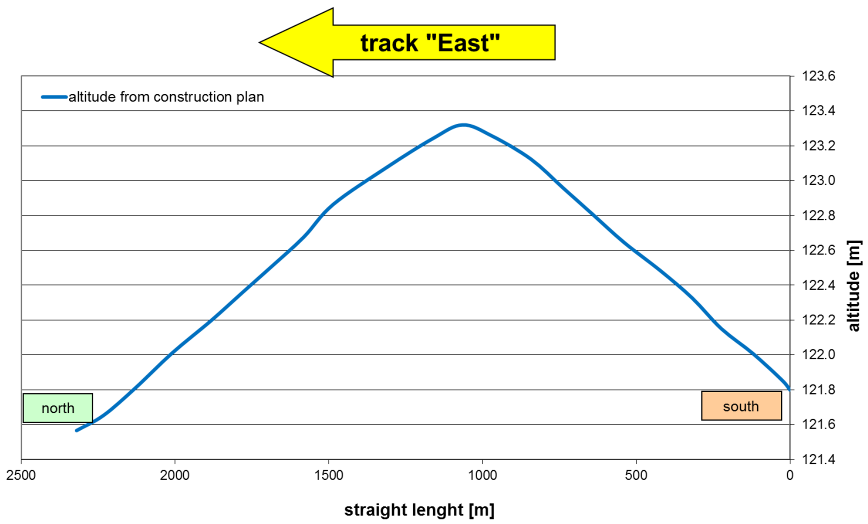
Figure 1: Krone standard trailer and Krone optimized trailer in a 40 ton GVW tractor-trailer combination

The two tested Schmitz Cargobull (SCB) trailers had both as common characteristic a box body, but were not comparable directly. The SCB standard trailer was a 3-axle construction equipped with a refrigeration body (2,60m vehicle width) and a refrigerating machine. The optimized trailer was a 2-axle construction equipped with a standard box body (2,55m vehicle width). So the difference in curb weight is about 2.5 t although the 2-axle trailer is equipped with side fairings. As a consequence from the 2-axle construction the GVW of the tractor-trailer configuration with the SCB optimized trailer was limited to 38 tons and needs tires for a load of 10 tons per axle. In the Klettwitz test the Goodyear Regio tires, which were not designed as low rolling resistance tires, were mounted on the SCB optimized trailer. The standard trailer was equipped with Michelin X Energy Saver Green tires (similar to the tires at the Krone trailer).

Figure 2: Schmitz Cargobull standard (40 ton GVW tractor-trailer combination) and Schmitz Cargobull optimized trailer (38 ton GVW tractor-trailer combination)

2.3. Test track

All measurements were done at the DEKRA test oval. This test circuit next to the city of Berlin consists of two 2300m long straight sections and two parabolic steep turns. The curve radius is 160m; the whole length of one lap is 5800 m. For the tested unladen HDV configuration the lengths of the straights allowed for a coast down from 85km/h to about 35 km/h. The parabolic steep turns allow for maintaining full vehicle speed (90km/h) throughout the entire cornering which is an important boundary condition for the execution of constant speed tests as proposed for the future HDV CO2 certification. **Figure 3** gives a picture of the test track location and the altitude profiles of the two straights from the construction plan. The maximum height difference within a single straight is at about 2m, the maximum road gradient is at about 0.2%. This altitude profile was considered in the evaluation of the driving resistance tests.



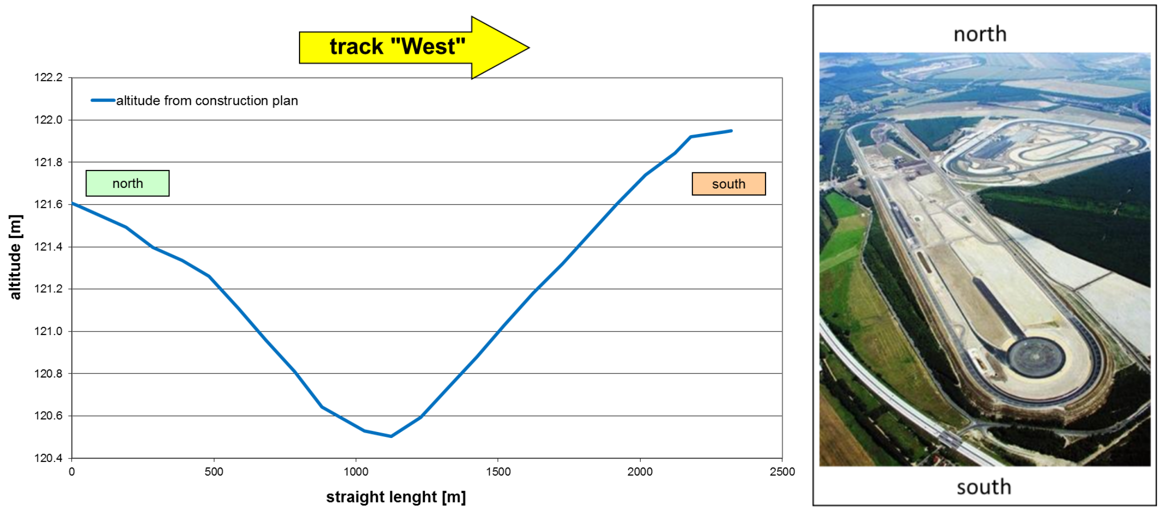


Figure 3: DEKRA test track and altitude profile of the straight sections „east“ and „west“

2.4. Instrumentation

Both tractors were equipped with an AIC Swissline 6004 fuel value amount measurement system. From the measured fuel volume flow, the fuel temperature, the diesel density, and the fuel mass flow have been calculated. The system was combined with a Racelogic VBOX GPS system, a CANBUS analyzer and a data logging system. Additionally, wind speed and direction sensors (anemometers) were installed at the roof of the tractors. The position of the anemometer on Actros A was calibrated to a position where the measured air flow velocity is identical to vehicle speed at wind still conditions. **Figure 4** shows the position of the anemometer at tractor A. To the right of Figure 4 a CFD simulation of a tractor with a roof fairing at a velocity of 80 km/h is shown. It can be seen, that the gradient of wind speed is very steep from the surface of the roof fairing towards the flowing air. At higher distances to the surface the velocity is higher than the velocity of the undisturbed air due to the redirection around the body. Very close to the surface the velocity is lower than the velocity of the undisturbed air due to the friction of the flow. Between these distances a narrow area exists, where the wind speed is similar to the undisturbed speed. To capture the actual undisturbed velocity of the wind, the instrumentation would need to be several meters in front or above of the vehicle and is not practicable for type approval test setup. The calibration of the position of the instrument on tractor A was performed by Daimler. The anemometer for tractor B was mounted directly on the test track and was not positioned exactly in the velocity-neutral area (**Figure 5**). Thus, a calibration factor was used, obtained by comparison to the wind speed measured on tractor A when driving on the test track. During all tests the distance between the test vehicles was several hundred meters to avoid influences on the air flow from one vehicle to the other.

Due to the slightly higher position of anemometer on Actros B, the measured velocity was 8% higher than vehicle speed measured at wind still conditions. Thus the measured wind speed at tractor B was corrected by a factor 0.926.

The velocities measured onboard have also been compared to the sum of vehicle velocity and the wind speed measured beside the vehicle on the ground. The agreement of the measured velocities was reasonable (see chapter 3). In all instances the wind speed and vehicle speed were added as vectors considering the direction of wind and the moving direction of the vehicle.

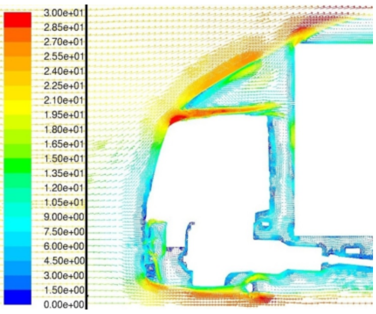


Figure 4: GILL USA 2D at tractor A **Figure 5:** METEC USA 3D at tractor B

All parameters which were logged (1 Hz resolution) during each test run are shown in **Table 2**.

Table 2: Measured parameters during the test runs at the DEKRA test track

VBox & USA datasets		CANBUS datasets	
consecutive number	Description	consecutive number	Description
1	Sattelites quantity	9	Torque
2	Time	10	Engine speed
3	Latitude	11	Temp. cooling water
4	Longitude	12	Gear
5	Speed GPS	13	Temp. gearbox oil
6	Height	14	Speed CANBUS
7	Speed Wind USA	15	Ambient temperature
8	Alpha Wind	16	Fuel temperature
		17	atmospheric pressure
		AIC Swissline 6004	
		18	fuel volume flow

2.5. Test matrix

The test matrix was designed to allow the analysis of following questions:

A) <u>Related to the test procedure</u>

A-1) Sensitivity of the measured differences between standard and optimized trailers as well as tire combinations to the tractor used (it is important to define the future test conditions for trailers in the test procedure)

→ Measure the aerodynamic drag with different tractor configurations (roof fairing positions varied)

A-2) Repeatability and sensitivity of the entire test procedure

→ Repetition of the tests on different days with the same settings

A-3) Possible options to improve and/or simplify the test procedure

→ Perform different test procedures (coast down and constant speed with different target speeds) with several truck and trailer combinations

B) Related to the testing of the fuel saving potential of existing technologies

B-1) Possible reductions in aerodynamic drag and rolling resistance by application of existing technology against the *baseline* products

→ Measurement of standard trailers and optimized trailers under comparable conditions (same tractor, same ambient conditions, same preconditioning, etc.)

B-2) Effects on the fuel consumption in different traffic situations and comparison of these results with results obtained by the manufacturer during real world driving

→ Results from B-1) were used as input to the simulation tool. Simulation of the fuel consumption for the tractor – trailer combinations in different test cycles

All of the tractor and trailer combinations, test runs and test conditions are shown in **Table 3**.

Table 3: Test Matrix for the test runs at the DEKRA test track

data ID	date	tractor	tractor aero settings	trailer	loading	tires semitrailer	mass vehicle	rotational mass wheels	weather	test method
[#]	[dd/mm]	[A/B]	[std/mod]	[make version]	[empty/loaded]	[make / model]	[kg]	[kg]	[ ]	[CS/CD]
1	27/09	A	std	Krone Std	empty	Michelin X Energy Saver	14900	830	dry	CD
2	27/09	B	std	Krone Opt	empty	Michelin X Energy Saver	15410	830	dry	CD
3	28/09	A	std	Krone Opt	empty	Michelin X Energy Saver	15330	830	dry	CD
4	28/09	B	std	Krone Std	empty	Michelin X Energy Saver	14840	830	dry	CD
5	29/09	B	std	SCB Opt	empty	Goodyear Regio	14715	700	dry	CD
6	30/09	A	std	SCB Std	empty	Michelin X Energy Saver	17095	830	dry	CD
7	30/09	B	std	SCB Opt	empty	Goodyear Regio	14645	700	dry	CD
8	03/10	A	mod	Krone Std	empty	Michelin X Energy Saver	14875	830	dry	CD
9	03/10	A	mod	SCB Std	empty	Michelin X Energy Saver	16990	830	dry	CD
10	03/10	B	std	SCB Std	empty	Michelin X Energy Saver	17025	830	dry	CD
11	03/10	B	std	Krone Std	empty	Michelin X Energy Saver	14850	830	dry	CD
12	04/10	A	mod	Krone Std	empty	Michelin X Energy Saver	14805	830	dry	CD
13	04/10	A	mod	Krone Opt	empty	Michelin X Energy Saver	15270	830	dry	CD
14	04/10	B	std	Krone Opt	empty	Michelin X Energy Saver	15315	830	dry	CD
15	04/10	B	std	Krone Std	empty	Michelin X Energy Saver	14780	830	dry	CD
16	05/10	A	std	Krone Std	empty	Michelin X Energy Saver	14735	830	dry	CD
17	05/10	B	std	Krone Opt	empty	Michelin X Energy Saver	15245	830	dry	CD
18	06/10	A	std	Krone Std	loaded	Michelin X Energy Saver	34515	830	dry/windy	CD
19	06/10	B	std	SCB Std	empty	Michelin X Energy Saver	17165	830	dry/windy	CD
20	07/10	A	std	Krone Std	loaded	Michelin Regio	34445	830	slightly wet	CD
21	07/10	B	std	SCB Std	empty	Michelin X Energy Saver	17095	830	slightly wet	CD
22	10/10	A	std	SCB Opt	empty	Goodyear Regio	14610	700	rainy/windy	CD
23	10/10	B	std	SCB Std	empty	Michelin X Energy Saver	17060	830	rainy/windy	CD
24	11/10	A	std	Krone Std	loaded	Michelin Regio	34340	830	wet/windy	CD
25	11/10	B	std	Krone Opt	empty	Michelin X Energy Saver	15350	830	wet/windy	CD
26	12/10	A	std	Krone Std	loaded	Michelin Regio	34280	830	wet/windy	CD
27	12/10	B	std	Krone Opt	empty	Michelin X Energy Saver	14770	830	wet/windy	CD
28	27/09	A	std	Krone Std	empty	Michelin X Energy Saver	14900	830	dry	CS
29	27/09	B	std	Krone Opt	empty	Michelin X Energy Saver	15410	830	dry	CS
30	28/09	A	std	Krone Opt	empty	Michelin X Energy Saver	15330	830	dry	CS
31	28/09	B	std	Krone Std	empty	Michelin X Energy Saver	14840	830	dry	CS
32	29/09	A	std	SCB Std	empty	Michelin X Energy Saver	17200	830	dry	CS
33	29/09	B	std	SCB Opt	empty	Goodyear Regio	14715	704	dry	CS
34	04/10	A	mod	Krone Std	empty	Michelin X Energy Saver	14805	830	dry	CS
35	04/10	A	mod	Krone Opt	empty	Michelin X Energy Saver	15270	830	dry	CS
36	04/10	B	std	Krone Opt	empty	Michelin X Energy Saver	15315	830	dry	CS
37	04/10	B	std	Krone Std	empty	Michelin X Energy Saver	14780	830	dry	CS
38	05/10	A	std	Krone Std	empty	Michelin X Energy Saver	14735	830	dry	CS
39	05/10	B	std	Krone Opt	empty	Michelin X Energy Saver	15245	830	dry	CS
40	06/10	A	std	Krone Std	loaded	Michelin X Energy Saver	34515	830	dry/windy	CS
41	06/10	B	std	SCB Std	empty	Michelin X Energy Saver	17165	830	dry/windy	CS
42	10/10	A	std	SCB Opt	empty	Goodyear Regio	14610	700	rainy/windy	CS
43	10/10	B	std	SCB Std	empty	Michelin X Energy Saver	17060	830	rainy/windy	CS
44	11/10	A	std	Krone Std	loaded	Michelin Regio	34340	830	heavy cross wind	CS
45	11/10	B	std	Krone Opt	empty	Michelin X Energy Saver	15350	830	wet/windy	CS

SCB…Schmitz Cargobull
Std…Standard trailer
Opt…Trailer with aerodynamic optimization
CS….Constant speed
CD…Coast down

Standards for the test runs coast down (CD) and constant speed (CS)

To have a solid basis for the analysis of the repeatability standard test sequences have been defined which were measured with each tractor-trailer combination similarly. The number of repetitions of these sequences varied depending on the task the tractor-trailer combination was measured for (e.g. many repetitions for the analysis of the repeatability). The team attempted to get at least two repetitions per tractor-trailer combination. The weather conditions from

October 6^{th} to the 10^{th} made it such that for some tractor-trailer combinations only one test sequence was possible under valid weather conditions (see Table 3).

The standard sequence (Sequence 1) for the **constant speed measurements** was as follows:

1.1. 60 minutes constant speed 20 km/h

1.2. 40 minutes constant speed 50 km/h

1.3. 40 minutes constant speed 75 km/h

1.4. 40 minutes constant speed 88 km/h

1.5. 1x coast down track east (to cross-check conditions with coast down sequence)

1.6. 1x coast down track west (to cross-check conditions with coast down sequence)

The standard sequence for the **coast down tests** was as follows:

2.1 30 minutes constant speed 85 km/h (warm up)

2.2 Measuring tire temperatures on the tractor and the trailer

2.3 8 consecutive coast downs (acceleration in the turns, deceleration on the straight section resulting in 4 coast downs east and 4 coast downs west)

2.4 10 minutes constant speed 85 km/h (to maintain the tire temperature levels for the entire set of coast downs)

2.5 8 consecutive coast downs (acceleration in the turns, deceleration on the straight section resulting in 4 coast downs east and 4 coast downs west)

2.6. Calculation of the driving resistances

The test results from

- Coast down tests
- Constant speed tests

were used to calculate the driving resistances for the tractor-trailer combinations. The evaluation followed different methodologies described in (Rexeis, 2011). First, the different options for evaluation were performed to derive results of the sensitivity of the driving resistances on the calculation method.

2.6.1 Coast down tests

The driving resistance force consists of rolling resistance, air drag, acceleration resistance and gradient resistance:

$$F_{res} = F_{roll} + F_{air} + F_{acc} + F_{grd}$$

with: F_{res} .... total driving resistance [N]

F_{roll} .... rolling resistance [N]

F_{air} .... air drag [N]

F_{acc} .... acceleration resistance [N]

F_{grd} .... gradient resistance [N]

The goal of the vehicle tests was mainly to obtain the air resistance value. In the procedure suggested for the future European HDV CO_2 testing the rolling resistance shall be calculated from the tire rolling resistance coefficient (RRC) measured from the standardized drum test procedure ISO 28580. The total rolling resistance however, was also evaluated from the coast down tests and from the constant speed tests to obtain more data to test the correlation between the RRC value from the drum test and the rolling resistance value gained from vehicle tests on the test track[3].

In the coast down tests the sum of forces is zero (neutral gear position and disengaged clutch). Thus, the sum of rolling resistance, air drag and gradient resistance has to be equal to the acceleration resistance.

$$F_{res} = 0 = F_{roll} + F_{air} + F_{acc} + F_{grd} \rightarrow F_{acc} = -(F_{roll} + F_{air} + F_{grd})$$

$$F_{acc} = (m_{tot} + m_{rot}) \times \frac{\Delta v}{\Delta t}$$

With $m_{vehicle}$ .... mass of the vehicle (including fuel and driver) [kg]

m_{load} .... mass of the payload [kg]

m_{tot} .... = $m_{vehicle}$ + m_{load}. The total mass of vehicle and payload was obtained by weighing the tractor and trailer at the test track for all measured variations. [kg]

m_{rot} .... equivalent mass of rotating components. Here, only the wheels have been considered with 83 kg per wheel and a total of 10 wheels (or 8 wheels for the optimised Schmitz Cargobull trailer combination). [kg]

v .... velocity of the vehicle [m/s]

t .... time [s]

In the coast down evaluation velocity intervals of Δv = 8 km/h from 82 to 42 km/h have been used for the calculation, resulting in average velocities of the intervals between 78 and 38 km/h.

To obtain correct results for the air drag and the rolling resistance, the force to overcome road gradients has to be subtracted:

$$F_{acc} + m_{tot} \times g \times \sin\alpha = -(F_{roll} + F_{air})$$

$$\alpha = \arctan\left(\frac{\Delta h}{\Delta s}\right)$$

With h .... altitude [m]

s .... distance driven [m]

For realistic road gradients sinα is similar to Δh/Δs:

$$F_{acc} + m_{tot} \times g \times \frac{\Delta h}{\Delta s} = -(F_{roll} + F_{air})$$

[3] Further data for this correlation shall be gathered in 2012 from a pilot test phase of the European test procedure to establish sound correction factors for the RRC values from the drum test (if necessary).

The split into air resistance and rolling resistance is based on the assumption that the rolling resistance (F0) is independent of the vehicle speed and air resistance depends on v^2. This simplification seems to be reasonable for HDVs and is necessary to obtain stable results from the data analysis (Rexeis, 2011):

$$F_{roll} + F_{air} = F0 + F2 \times \mathrm{v}^2$$

The rolling resistance depends on the temperature of the tires and the air resistance depends on the air density, which depends on the ambient temperature and pressure. Since these parameters vary over the time and over different days, the test results are corrected for these influences and normalized to standard conditions:

$$F_{air-norm} = F_{air} \times K_{air} = (C_d \cdot A_{cr} \cdot \frac{\rho_{air,ref}}{2} \cdot \mathrm{v}_{veh}{}^2)$$

K_{air} corrects according to the ideal gas equation for the differences between air density during measurement and standard conditions (1bar, 20°C):

$$K_{air} = \frac{1000 \cdot T_{amb}}{p_{amb} \cdot 293{,}15}$$

The measured rolling resistance is corrected with an empirical formula for temperature influences:

$$F_{roll-norm} = F_{roll} \times K_{roll}$$

$$K_{roll,j} = 1 + k \cdot (T_{amb} - 293{,}15)$$

with C_d............. air drag coefficient [-]

A_{cr}............. cross sectional area of the vehicle [m²]

$\rho_{air,ref}$......... air density at reference conditions, 1,188 kg/m³

v_{veh}........... vehicle velocity [m/s]

K_{roll}........... correction factor for rolling resistance [-]

K_{air}............ correction factor for air resistance [-]

k............... correction coefficient for influence of ambient temperature on tire rolling resistance, 0.006 [K^{-1}] (source: ISO 28580)[4]

T_{amb}........... ambient temperature [K]

p_{amb}........... ambient pressure [mbar]

Figure 6 shows the results for a set of coast down tests with the Actros and Schmitz Cargobull standard trailer.

..

[4] From the experience in the FAT projects with the outdoor measurements it is problematically to use the correction factor according to ISO 28 580 which seems to be valid only for the small ambient temperature range between 20°C and 30°C and the test conditions in indoor measurements. However, as this factor is the only reference available from literature, it was assessed to be more reasonable to apply it to all data than completely neglecting this influence. In this context a need for improvement of correction methods appears obvious.

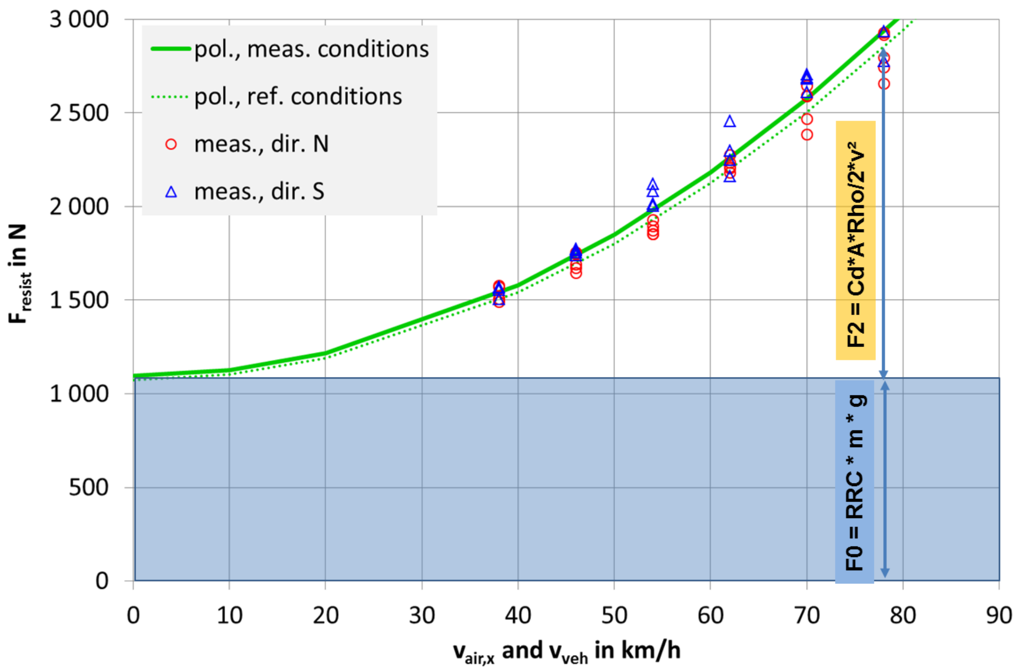


Figure 6: Example for measured driving resistances at a coast down with the Actros and Schmitz Cargobull standard trailer

2.6.2 Constant speed tests

The evaluation of the constant speed tests follows the fundamentals of vehicle dynamics as in the coast down tests. Contrary to coast down tests, the total driving resistance (F_{meas}) is gained from the measured fuel consumption[5] and, as an alternative, from the ECU reading.

$$F_{meas} = F_{roll} + F_{air} + F_{acc} + F_{grd}$$

Figure 7 shows the recorded power from the ECU in comparison to the power gained from the fuel flow measurement for four rounds on the test track at 90 km/h. The agreement between ECU data and fuel flow measurement was good. Since the ECU data for engine power is generally known to be not very accurate in actual vehicles, the fuel flow instrument was used in all further evaluations as the measured value for power.

[5] The measured fuel consumption in 1Hz is used to interpolate the engine power from the engine fuel map, which was measured for the Actros in the DG CLIMA project (Rexeis, 2011).

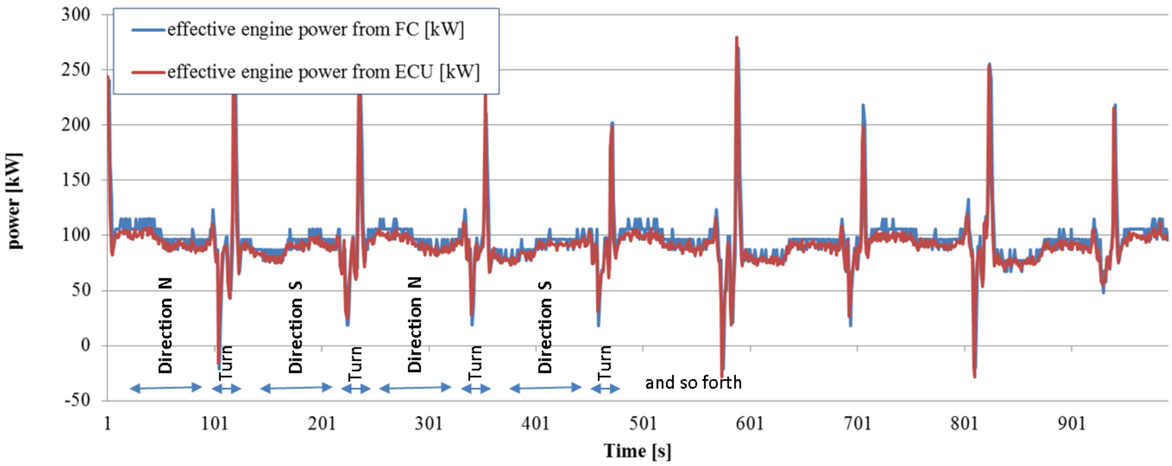


Figure 7: Engine power measured in constant speed test No. 28 in counterclockwise driving at 90 km/h in the first 1000 seconds

From **Figure 7** it can be seen, that the subtraction of the acceleration force and the road gradient related force is also necessary at constant speed driving since small variations in the vehicle speed and in the road gradient influence the measured force due to the high mass of the vehicle. Basically, the acceleration and road gradients would level out over longer tests if the entire test period can be used. Since the driving resistance during the turns increases, the evaluation is based only on the straight parts of the test track. Without correction in later type approval tests, accelerations may occur during the turns and decelerations on the straights , which could lead to tampering of the results. Thus, for the final test procedure the complete correction is suggested.

The average force F_{meas} and thus the acceleration and road gradients are calculated for 20 second intervals on the straight sections of the test track.

$$F_{roll} + F_{air} = F_{meas} - (F_{acc} + F_{grd})$$

$$F_{acc} = (m_{tot} + m_{rot}) \times \frac{\Delta v}{\Delta t}$$

The steps of the evaluation are similar to the methods explained for the coast down, i.e. subtraction of the force resulting from road gradients up to correction to standard ambient conditions.

The interpolation from the steady state engine map with the engine speed and the fuel mass flow results in the effective engine power. From the effective engine power, the power demand from the auxiliaries and losses in the transmission are subtracted. The necessary data to calculate these power losses for the Daimler Actros was already generated by extensive measurements in the DG CLIMA project (Rexeis, 2011). The method to obtain the driving resistances from the fuel flow measurement was the preferred method for an EU test procedure when the tests for the actual project were planned. Tests on a city bus in the DG CLIMA study as well as the results obtained here showed that uncertainties in the calculation of the power demand from auxiliaries seem to be too high to recommend this method for the final test procedure. Thus a direct torque measurement at the driven wheels is suggested. This method will need special torque measurement rims which were not available for the tests performed in this study.

2.6.3 Alternatives tested

The following variations of the "measured" vehicle velocity have been calculated for the aerodynamic drag:

- the relative velocity between the vehicle and the air in vehicle moving direction
- the relative velocity between the vehicle and the air in the resultant direction of wind and vehicle movement
- the vehicle velocity relative to the ground

2.7. Simulation of the fuel consumption

The simulation of the fuel consumption of the tractor-trailer combinations in real world driving cycles was performed with the vehicle longitudinal dynamics and emission model PHEM (Passenger car and Heavy duty Emission Model) from TUG. A detailed description of PHEM can be found in (Luz, 2009; Hausberger, 2009; Rexeis, 2009). The model has been developed since 1999 at TU Graz and was used for computing fuel consumption and pollutant emission values for cars, light commercial vehicles and HDV in EU projects (ARTEMIS, 2005; COST 346) and for the HBEFA (www.hbefa.net) and also for HDV in COPERT.

PHEM calculates the engine power in 1 Hz based on the given courses of vehicle speed (the "driving cycle") and road gradient based on the input data for the vehicle for the driving resistances and the losses in the transmission system. The 1 Hz course of engine speed is simulated based on the transmission ratios and a driver-gear-shift model. The driver model follows the defined test cycle in principle exactly. If the actual engine power is not sufficient to follow the target speed in the gear with the highest power at the actual speed, the vehicle drives with engine at full load. This leads to reductions against the target vehicle speed. In these situations PHEM keeps the trip distance constant, i.e. the travel time increases.

From the 1Hz data on engine power and engine speed the fuel consumption is computed from the engine map, which is also provided as model input.

A schematic of the PHEM model as used for the calculation of the emission factors for the HBEFA 3.1 is shown in **Figure 8**.

In the actual simulation, the following steps were taken:

1) Compute aerodynamic drag and resulting Cd value from the constant speed tests for the trailers with the tractor variations for normalized conditions → Cd*A as model input
2) Compute the rolling resistance from the RRC values from the drum tests for the tire variations used (different tires on tractor and trailers and axle load dependency of the RRC are considered) → RRC as model input
3) Apply the detailed tractor data from the DG CLIMA project as model input (engine fuel consumption map, gearbox efficiency map, power demand data for the auxiliaries)
4) Run the model PHEM with the input data

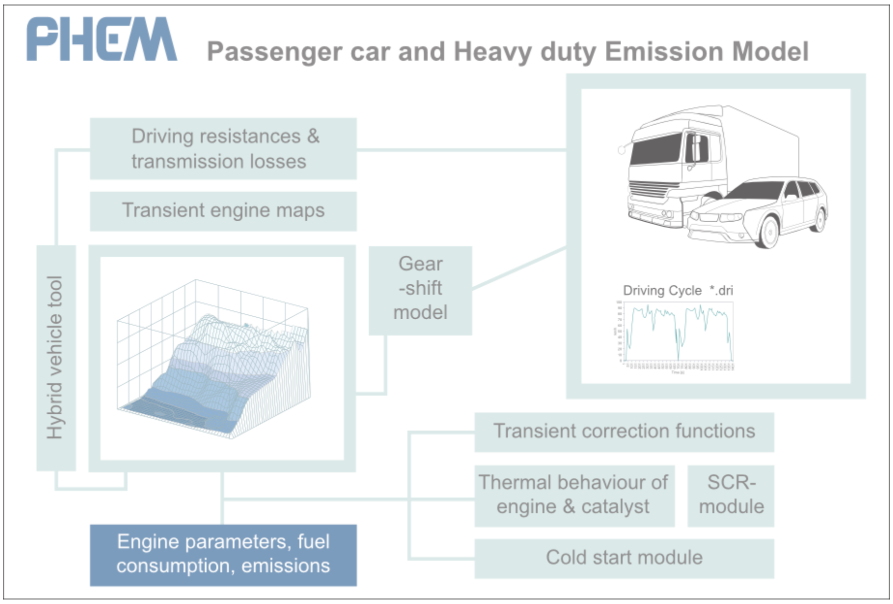


Figure 8: Scheme of the emission model PHEM

As shown in Figure 8 PHEM also includes transient correction functions for pollutant emissions and a cold start tool which is based on simplified heat balances and simulates the temperatures of exhaust gas after treatment systems and the resulting conversion efficiencies. Since the simulation of pollutant emissions was not relevant here, these tools were not activated. Also, the model elements “Hybrid vehicle tool” and “Cold start”, which are by default available in the current version of the PHEM software, have not been used in the context of the actual project.

The main components of the simulation in PHEM are summarized below. **Equation 1** shows the components considered for calculating the power demand.

Equation 1: Calculation of the engine power demand

$P_e = P_{roll} + P_{air} + P_{acc} + P_{gradient} + P_{transm.} + P_{aux.}$

The calculation of the single components is described shortly in the following.

Equation 2: Power demand to overcome the rolling resistance [W]

$$P_{roll} = (m_{Vehicle} + m_{Load}) \times g \times (\mathrm{Fr}_0 + \mathrm{Fr}_1 \times \mathrm{v} + \mathrm{Fr}_4 \times \mathrm{v}^4) \times \mathrm{v}$$

With $m_{vehicle}$ .... mass of the empty vehicle in [kg]

m_{Load} .... mass of driver, passengers and/or payload in [kg]

Fr_0, Fr_1, Fr_4 ...... Rolling resistance coefficients [-], [s/m], [s^4/m^4]

v....................... velocity [m/s]

The parameter Fr_0 refers to the RRC (rolling resistance coefficient) as discussed in this study. As already mentioned for HDVs, the speed dependency of the rolling resistance is neglected, i.e. the values of Fr_1 and Fr_4 are set to zero.

Equation 3: Power demand to overcome the air resistance [W]

$$P_{air} = C_d \times A_{Cs} \times \frac{\rho}{2} \times v^3$$

With C_d..................... air resistance coefficient [-]

A_{Cs} .... Cross sectional area [m²]

ρ...................... density of the air [kg/m³]

Equation 4: Power demand for acceleration [W]

$$P_{acc} = (m_{Vehicle} + m_{Rot} + m_{Load}) \times a \times v$$

With a .... acceleration of the vehicle [m/s²]

m_{Rot} .... equivalent mass for taking the inertia of rotational accelerated parts into consideration (in PHEM these parts are summarized in three groups (wheels, gearbox parts, engine)

The equivalent mass is calculated from the inertias and the transmission ratios.

Equation 5: Calculation of the equivalent mass for rotational accelerated parts

$$m_{rot} = \frac{I_{Wheels}}{r_{Wheel}^{2}} + I_{mot} \times \left(\frac{i_{Axle} \times i_{Gear}}{r_{Wheel}} \right)^2 + I_{transmission} \times \left(\frac{i_{Axle}}{r_{Wheel}} \right)^2$$

Equation 6: Power demand to overcome the road gradient [W]

$$P_{gradient} = (m_{Vehicle} + m_{Load}) \times g \times Gradient \times 0.01 \times v$$

With Gradient.......Road gradient in %

Equation 7: Power demand from auxiliaries [W]

$$P_{Auxiliaries} = P_0 \times P_{Rated}$$

With P_0..........Ratio of power demand from auxiliaries to rated engine power [-]

P_{rated}......Rated power of the engine [W]

Alternatively, the course of power consumption of the auxiliaries can be specified in the input driving cycle.

Equation 8: Power losses in the transmission system [W]

$$P_{transmission} = A_0 \times (P_{Differential} + P_{Gear\,i})$$

With A_0 .... Factor for adjusting the losses to single vehicles.

In PHEM the losses in the gearbox and the differential are calculated either using the implemented default functions (based on a dependency on transmission ratio, the transmitted torque and the rotational speed) or computed from user defined maps (input data). In this study fixed efficiency values for the single gears and for the differential were used.

The actual engine speed depends on the vehicle speed, the wheel diameter and the transmission ratios of the axle and the gearbox.

Equation 9: Calculation of the engine speed

$$n = v \times 60 \times i_{axle} \times i_{gear} \times \frac{1}{D_{wheel} \times \pi}$$

with: n............... engine speed [rpm]

v............... vehicle speed in [m/s]

i_{axle} .... transmission ratio of the axle [-]

i_{gear} .... transmission ratio of the actual gear [-]

D_{wheel} .... Wheel diameter [m]

In the simulations standard gear shift model as developed for the calculation of the emission factors for the HBEFA 3.1 was applied.

3. RESULTS

The results for aerodynamic drag, rolling resistance and fuel consumption are described below.

3.1. Aerodynamic drag

The repeatability was compared between coast down and constant speed tests with the different approaches for wind speed data. Then the sensitivity was tested for the measured differences between the trailer variations with different tractor configurations. The most robust combination of test method and evaluation was then used to produce the final results for the aerodynamic drag of the different trailers.

3.1.1 Comparison of coast down and constant speed tests

The analysis of the repeatability gave a slightly better repeatability of constant speed tests as compared to coast down tests. Most valid repetitions were performed for the Krone semi-trailers. The evaluation results for the option considering the wind speed in driving direction is shown in **Table 4**. The standard deviation was found to be below 4% for the coast down tests and below 3% for the constant speed tests. For the optimized Schmitz Cargobull however, the coast down tests resulted in a standard deviation of 14%, but only two repetitions were performed with this set up. During the constant speed tests with the Schmitz Cargobull and also during the coast down tests with the standard Schmitz Cargobull trailer the weather conditions varied in terms of dry and wet road surfaces and high and low wind speeds. Due to the restricted test time only one test result per vehicle setting at comparable favorable ambient conditions is available from these tests, and thus no conclusion on the repeatability of these test setups is possible.

Table 4: Average driving resistance coefficients from constant speed tests and from coast down tests. The standard deviation is shown for the F2.

Trailer	Method	nr. of valid test series	F0 [N]	F2 [Ns²/m²]	Std Dev F2 %	95% Conf. FC
			[N]	[N]	[%]	[%]
Krone Standard	Constant speed	2	792	3.95	2.6%	3.5%
Krone Optimized	Constant speed	2	870	3.71	1.5%	2.0%
Krone Standard	Coast down	3	1029	3.40	3.6%	4.1%
Krone Optimized	Coast down	3	1022	3.16	3.3%	3.8%
Schmitz Optimized	Coast Down	2	1103	3.45	13.6%	18.9%

The comparison of F2 values from constant speed and coast down tests gives differences in the range of 15% with in general higher value from constant speed tests. This means the determined CdxA-value differs in the same range between the measurement procedures.

Figure 9 shows the driving resistances computed for the Krone trailers with the Actros tractors at a constant speed of 88 km/h and using the resistance coefficient values in Table 4. At 88 km/h the air drag represents approximately 70% of the total resistance for the tested empty vehicle. At 50 km/h this value drops to approximately 40%. In average real world driving conditions the share of air resistance on the total engine work demand is certainly lower than the shares given above due to the additional influences of road gradients, decelerations and internal power losses in the vehicle (see chapter 3.4).

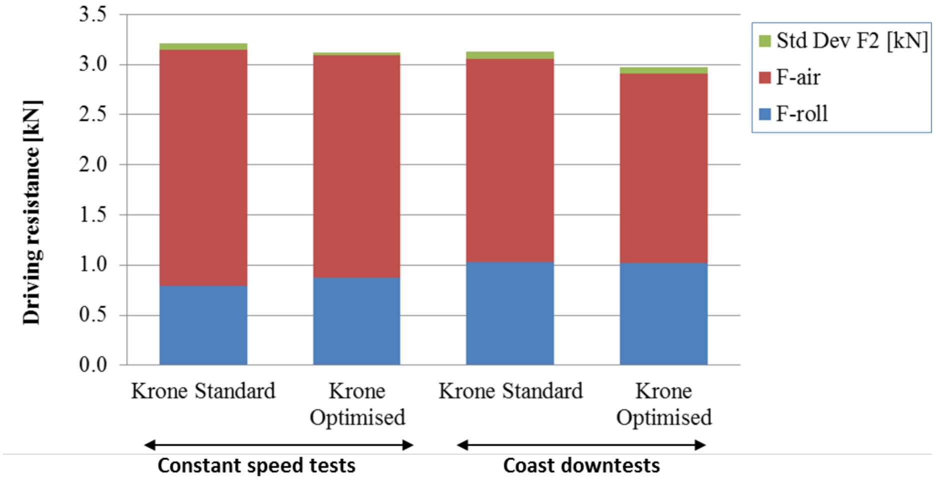


Figure 9: Average driving resistances at 88 km/h derived from constant speed tests and from coast down tests for the Krone trailers. The standard deviation is shown for the F2 (wind speed in driving direction included into the evaluation)

For the tested Krone trailers the reduction in air resistance for the optimized trailer as compared to the standard trailer was measured to be 4% from the constant speed and 9% from the coast down tests[6]. This great difference shows the main challenge of the test methods. A difference of 4% in CdxA is assessed to be the more realistic number.

Looking at the 95% confidence intervals, the uncertainty from the coast down tests with the Schmitz Cargobull trailers was clearly higher than the difference measured between the trailer variations. As a conclusion a much higher number of tests than the 2x8 repetitions seems to be necessary for reliable air resistance values from coast down testing.

For the constant speed method with two or more test series available no such worse repeatability was found, but the limited number of comparable tests series does not allow for a final conclusion. We assume that using a torque measurement at the wheel instead of the method based on the fuel flow will lead to a better repeatability since the uncertainty from the variable operation of the auxiliaries would be eliminated.

3.1.2 Influence of the tractor design

Analyzing the differences in the aerodynamic drag between the Actros A and B with the same trailer a T-test gave a 77% probability that the two tractors used were identical in their

[6] The differences between the trailers are discussed in detail in section 3.1.4, this section focuses on the comparison of the test methods.

standard configurations. Since the Actros are the same make and model this was not surprising. However, the number of available tests repetitions is too low to allow for more statistical significant results.

To test the sensitivity of the absolute and relative difference between the aerodynamic drag from two trailer variants and the design of the tractor, one Actros was modified such that the side fairings between the tractor and trailer were removed and the roof fairing was lowered to the flat position. With this aerodynamically unfavorable setting, the tests were repeated with both Krone trailers. The analysis showed only minor differences in the resulting change of the aerodynamic drag ($Cd_{opt.}/Cd_{standard}$), see **Table 5**.

Table 5: Results for the aerodynamic drag for the Krone trailers from the constant speed tests for two settings of the tractor

		F2	Cd	Diff Cd	Delta Cd
		[Ns²/m²]	[-]	[-]	[-]
standard tractor	Krone Standard	3.90	0.691	-0.030	-4.3%
	Krone Optimized	3.73	0.661		
tractor with worse aerodynamic	Krone Standard	4.68	0.829	-0.027	-3.3%
	Krone Optimized	4.52	0.801		

Based on this small number of tests no final conclusions are possible since a higher difference may be masked by the uncertainty of the tests themself. However, at the moment it seems as if the tractor design has a small influence on the measured change in the aerodynamic drag. This would allow measurement of the Cd values of trailers without the need for a defined “standard tractor” as long as the reference trailer and the tested trailer are measured with the same tractor[7]. However, as criteria for approval of a tractor for testing with different trailer configurations, a definition of minimum sales numbers and design criteria for roof and side fairings is recommended to avoid having *special* designs for test tractors.

In any case the tests showed that aerodynamic features on the tractor have a very positive effect on the aerodynamic drag. Without roof and side fairings the Cd value would increase by approximately 20%.

3.1.3 Influence of wind velocity

Most days during the test campaign were relatively calm, but several days had higher wind speed. This data set was used to test the sensitivity of the results against wind speed. Tests No. 28 to 33 and 38 to 39 had low winds, while tests No. 41 to 44 had high winds. **Figure 10** shows the results for three trailer configurations. For each test the results are plotted for the evaluation method considering the wind speed in the vehicle driving direction and for the method using the vehicle speed only.

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[7] For the EU test procedure a “standard trailer” is defined for testing the air resistance from all tractors. Alternative trailer designs can be tested for their relative benefits as compared to the standard trailer.

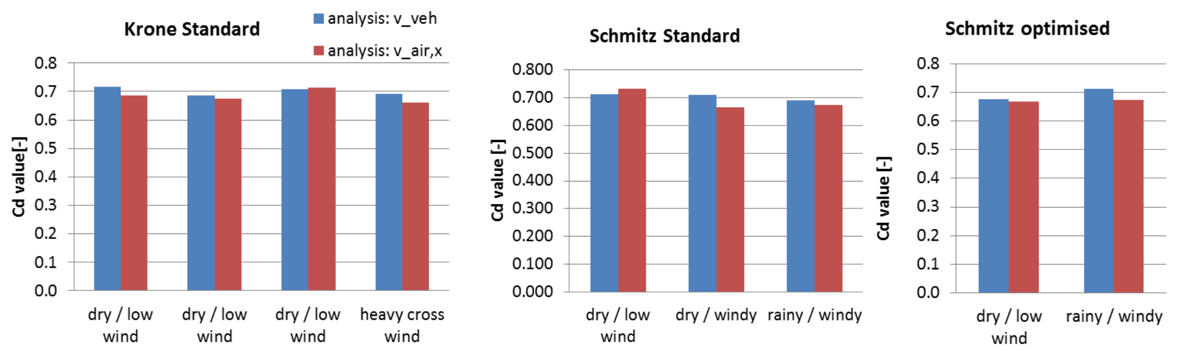

Figure 10: Cd values evaluated from constant speed tests at different wind conditions

The results from the constant speed tests in low wind conditions are not affected much if evaluated based on vehicle speed or on air inflow speed in the driving direction. The difference between both evaluation methods is in the range of the uncertainty of the calibration of the on-board anemometer.

In heavy wind conditions the evaluation method based on vehicle speed gives systematically lower Cd values than the method based on air inflow speed. This can be explained by the fact that at high vehicle speeds a certain increase of air inflow speed due to headwind causes a higher increase of air drag than the decrease of air drag due to tailwind on the back straight due to the quadratic influence of the wind speed.

An interesting result is also that no influence of potential side wind was found on the Cd value. From the literature a measureable increase in air resistance during cross winds was expected at least for the standard trailers. Since the wind conditions varied along the test track due to the woods and noise barriers and the analysis of the on-board anemometer data did not show the angle between the driving direction and the wind exactly, no numerical analysis of the influence of cross winds is possible.

The coast down tests seems to be more sensitive for higher wind speeds. Since the woods and noise barriers along the track protect from wind to a different degree in some areas, it seems to be logical that the wind conditions vary between the single velocity phases of the coast down test. These differences are not balanced out by measurements in both directions during coast downs. This can cause the higher sensitivity. Also, the influence of the method of how the wind data is taken into consideration in the test evaluation (only vehicle speed, wind in driving direction, resulting air speed) showed a higher influence for the coast down tests at high wind speeds than for the constant speed tests.

3.1.4 Results for the trailers

The more robust method to determine the air resistance seems to be the constant speed test, with or without consideration of the wind speed in vehicle driving direction. **Figure 11** compares the Cd values evaluated from constant speed tests and from coast down tests with the Krone standard trailer and with the Krone optimized trailer. For this evaluation the tests at low wind conditions were used.

From the constant speed tests, the average difference of the Cd values between the optimized and the standard trailer was found to be 4.3%. From the coast down tests, the scattering of the data points was larger, and the average reduction in Cd values from using the optimized trailer was approximately twice the value found with the constant speed tests.

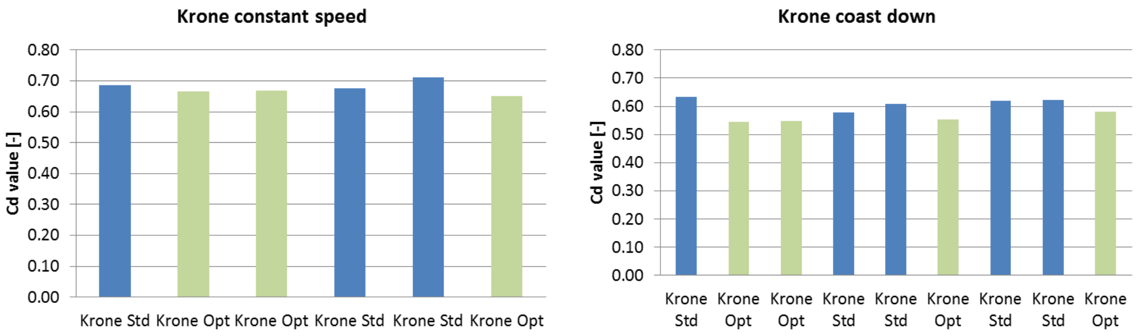

Figure 11: Cd values derived from constant speed tests and from coast down tests with the Krone standard trailer and with the Krone optimised trailer at low wind conditions (the average reduction found from constant speed tests is 4.3% in the Cd value)

Figure 12 shows the results for the Schmitz Cargobull trailers. The average reduction found from the constant speed tests was 4.2% and thus similar to the reduction found for the optimized Krone trailer. The data scatter in the coast down tests was highest for the Schmitz Cargobull tests. Depending on which pair of tests is selected, differences between +13% and -13% can be found between the two trailer types. This supports the argument that coast down tests would need to be based on a large number of tests to provide reliable results.

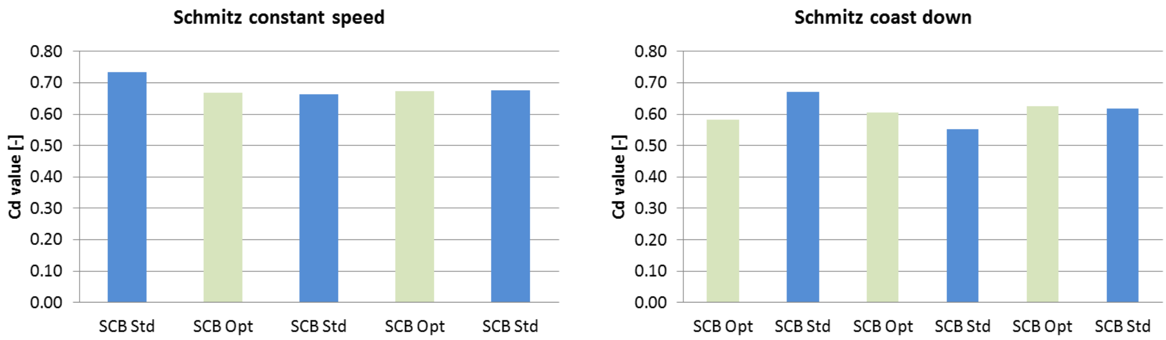

Figure 12: Cd values evaluated from constant speed tests and from coast down tests with the Schmitz Cargobull standard trailer and with the Schmitz Cargobull optimized trailer at low wind conditions (the average reduction found from constant speed tests is 4.2% in the Cd value)

3.2. Tire rolling resistance

The influence of tires was tested on the Krone standard trailer. To obtain more accurate results, the vehicle was loaded to 34.5 tons. Since the rolling resistance increases nearly proportionally with the axle load, a higher weight gives the rolling resistance a higher share of the total driving resistance and thus lowers uncertainties in the measurement.

Neglecting small driving forces such as bearing friction and residual braking forces, the tire rolling resistance coefficient (RRC) is calculated for the entire articulated truck by dividing the total rolling resistance force by the total vehicle load:

$$RRC = \frac{F_{roll}}{m_{tot} \cdot g}$$

For comparison the RRC values for the single tire models were measured by the tire manufacturers on the drum test stand according to ISO 28580. The according numbers are shown in **Table 6**.

Table 6: values according to ISO 28580

Tire make and model	Mounting position	RRC according to ISO 28580	Remarks
Continental HSL1 Ecoplus	tractor, front axle	0.00554	
Continental HDL1 Ecoplus	tractor, rear axle	0.00577	
Michelin X Energy Saver	trailer	0.00410	lowolling resistance technology
Michelin Regio	trailer	0.00570	

Then the rolling resistance for the articulated truck was calculated based on the RRC values from the drum test stand for each axle separately. The tires on the axles of the tractor were unchanged in the tests. Thus, the differences in the total RRC value for the articulated truck resulted from the three axles of the trailer only.

The results from the constant speed tests and the results derived from the tire test drum are quite similar in terms of absolute driving resistance (**Table 7**).[8] Also, the relative difference between the two tire models is within the uncertainty for the constant speed tests based on fuel flow measurement.

Table 7: Rolling resistance coefficient for the articulated truck [-] at reference conditions from the constant speed tests and derived from the drum test stand according to ISO 28580

Trailer tires	Total rolling resistance for the entire articulated truck	
	constant speed tests	calculated based on tire test drum RRC
Michelin X Energy Saver	0.00477	0.00490
Michelin Regio	0.00585	0.00580
Difference	*23%*	*18%*

3.3. Suggested improvements in the measurement procedure

The calculation of the forces at the drive wheels of the tractor from fuel flow measurement proved to have disadvantages in terms of the accuracy and the necessary effort to measure all

[8] The RRC values found at the test track in Klettwitz seem to be rather high, tests at Papenburg in the DG CLIMA project showed approximately 20% lower RRC values. Furthermore, the tires were rather new and thus had above-average RRC values.

In the derivation of the “real world” rolling resistance based on the RRC values from the tire test as specified in literature often correction factor is used, which shall convert the rolling resistance on the test drum to flat conditions. For the tire dimension used in this study this correction factor would be at 0,8. In this study this correction factor was not applied in order to meet the measured rolling resistance levels during the test conditions.

of the auxiliary loads and to assess the losses in the transmission. Therefore, attempts are being made to develop a torque measurement device for the wheels. Manufacturers of torque measurement equipment were contacted and seem to be optimistic that they will be able to produce a robust and cost-efficient torque measurement rim in 2012. This device shall be tested in a pilot phase of the EU test procedure. This instrumentation will most likely improve the accuracy for the constant speed tests.

In principle, splitting the total driving resistance into air and rolling resistance, two test velocities are sufficient. One velocity should be at the maximum governed speed of the HDV since the accuracy of the measurement devices is high at high loads. Having the second velocity at close to zero km/h would make the split into F0 and F2 most robust. Unfortunately, the measurement accuracy at very low speed is not very good. On the other hand, deviations at two high vehicle speeds have a bigger influence on the resulting air drag due to the leverage effect, which can be seen in **Figure 13**. A 10% error in the measurement at 60 km/h leads to approximately 40% deviation of the rolling resistance if no slower velocity is measured as well. This also influences the air resistance (here +/- 14%).

On the other hand, a 10% error at zero km/h causes 10% deviation in the rolling resistance and only approximately 3% deviation in the resulting air resistance. This leads to the idea measuring only at maximum vehicle speed and calculating the rolling resistance from the drum test. The main advantage would be a shorter test program. Also, this method would avoid the uncertainty presented by varying ambient conditions. Varying surface conditions on the test track affect the real rolling resistance in unknown ways. This unknown variability would be attributed to the Cd value if not corrected for in the RRC values from the drum test. This approach was tested with the data measured here. However, the repeatability was not improved against the standard constant speed method. Maybe test track specific correction factors for the drum RRC values could improve the situation. This may be further tested in the pilot phase of the test procedure.[9]

[9] The use of a fixed rolling resistance from the drum test in the test evaluation is only suggested for testing the difference in air drag of two trailer or body variations. In the evaluation procedure for the absolute cd-value of a truck the measured rolling resistance shall be used.

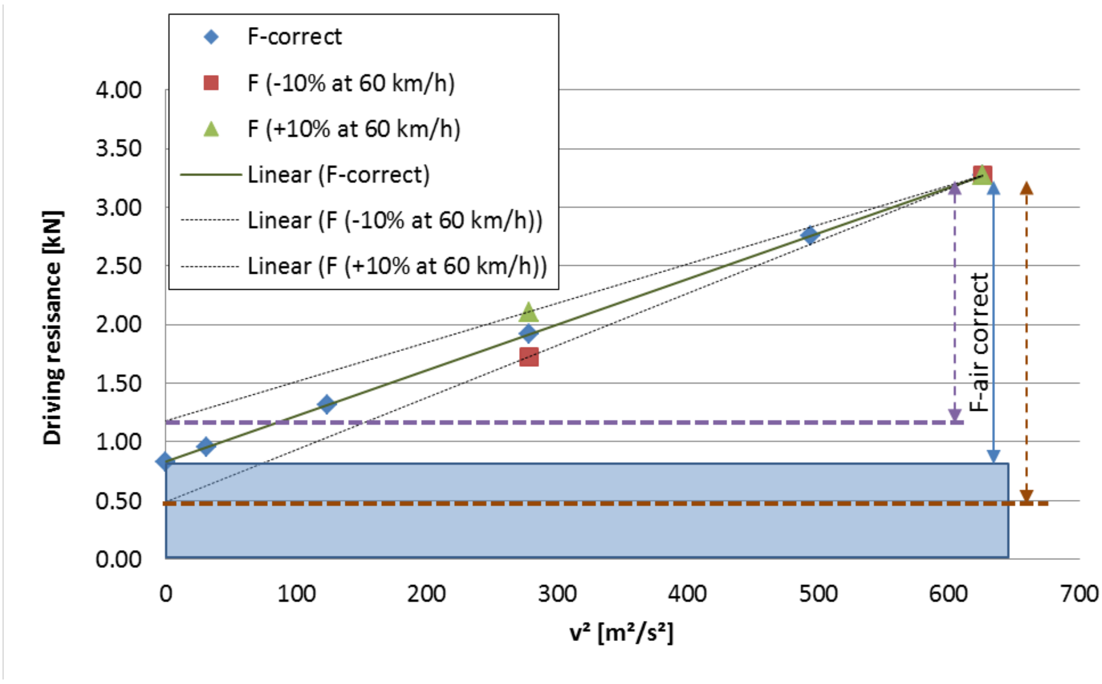

Figure 13: Graph of the influence of measured velocity on the uncertainty of the split between rolling resistance and air resistance

The measurement of the driving resistance from fuel flow has quite a high uncertainty at low velocities.

3.4. Effects on the fuel consumption of articulated trucks

The simulations were performed for a cycle mix of urban, road and motorway segments that was elaborated in the DG CLIMA project as first draft for Long Haul missions. The final cycle may look different, but the design of the draft cycle is quite realistic already. Long haul transport in Europe is characterized by high shares of highway driving at about 88 km/h (**Figure 14**).

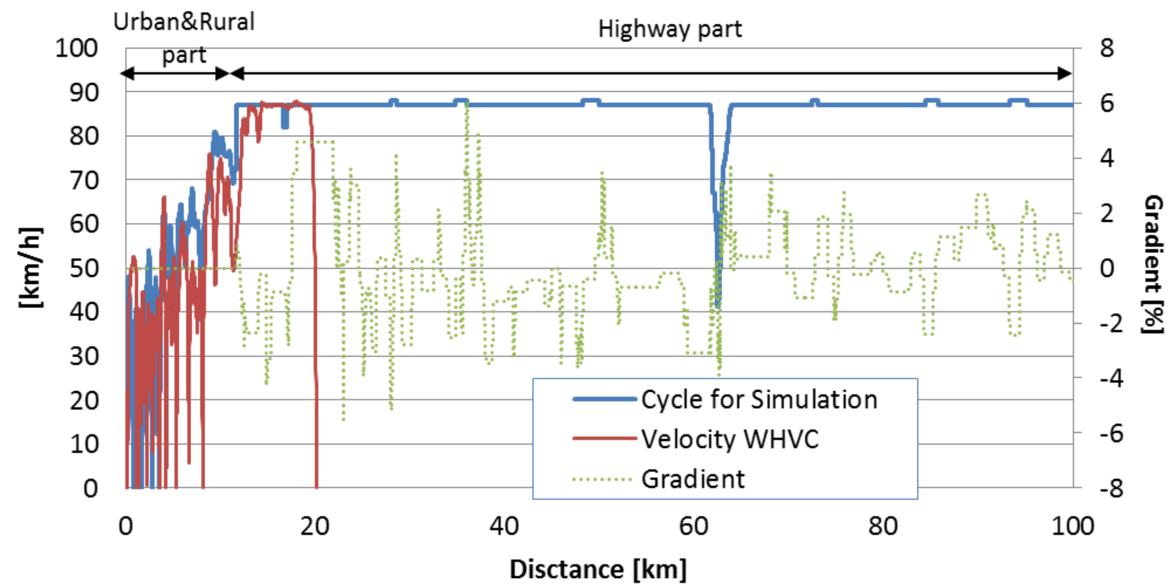

Figure 14: Test cycle used for the fuel consumption simulation of articulated trucks, including the road gradients and a comparison to the WHVC

During high road gradients the vehicle has to slow down due to the limited engine power. The PHEM model automatically adapts the engaged gear and also the speed profile to the maximum engine power available. **Figure 15** shows the target speed and the vehicle speed computed by PHEM for one of the articulated truck combinations with an average load. Fully loaded, the speed reductions are more pronounced, and the converse is true for an empty vehicle.

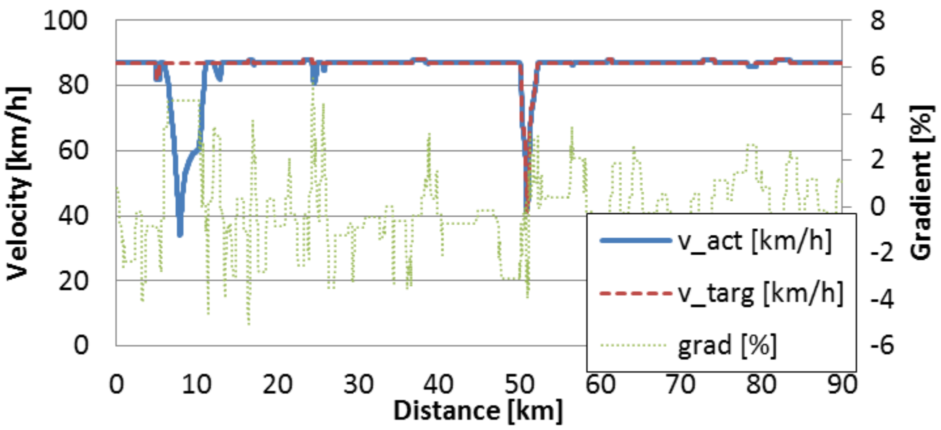

Figure 15: Target speed on the highway portion of the test cycle in comparison to the simulated vehicle speed for a tractor-trailer combination with an average load

The tractor-trailer combinations were simulated in empty conditions, with average loading (19.3 tons) and fully loaded (22.8 to 25t depending on the trailer type). The maximum payload is the difference between the vehicle weight and the maximum allowed gross vehicle weight and varies between the trailer types.

The simulations were done for the combinations shown in **Table 8**, each of them for empty, average and full loading conditions and for the Krone and Schmitz Cargobull trailers.

Table 8: Vehicle variations simulated

Tractor	Trailer	Trailer tires RRC	Comments
Actros without wind shield and flaps	Standard	High	Not common
Actros in standard configuration	Standard	High	European standard
Actros in standard configuration	Standard	Low	
Actros in standard configuration	Optimized	High	
Actros in standard configuration	Optimized	Low	

This leads to the input data shown in **Table 9** and **Table 10**. For the optimized Schmitz Cargobull trailer there is currently only one tire model available that is capable of the increased axle load that results from the two axle configuration. This tire model has rather high RRC values (marked as “high RRC” in Table 10). For a complete evaluation of this trailer low rolling resistance tires were applied in the simulation, since in the future more manufacturers may offer tires for increased axle loads if this concept gains higher market share.

Table 9: Setup for the articulated truck combinations simulated with the Krone trailers

semitrailer	tractor	trailer tires	variation #	empty vehicle vehicle mass [kg]	empty vehicle RRC [-]	average payload (19302kg) vehicle mass [kg]	average payload (19302kg) loading [kg]	average payload (19302kg) RRC [-]	maximum payload vehicle mass [kg]	maximum payload loading [kg]	maximum payload RRC [-]	cd (A=9,5m²) [-]	rotational equivalent mass [kg]
Krone Std	original	low RRC	1	14975	**0.00559**	34277	19302	**0.00490**	40000	25025	**0.00482**	**0.691**	830
Krone Opt	original	low RRC	2	15475	**0.00554**	34777	19302	**0.00489**	40000	24525	**0.00482**	**0.661**	830
Krone Std	high cd	low RRC	5	14975	**0.00559**	34277	19302	**0.00490**	40000	25025	**0.00482**	**0.829**	830
Krone Std	original	high RRC	6	14975	**0.00659**	34277	19302	**0.00578**	40000	25025	**0.00569**	**0.691**	830
Krone Std	high cd	high RRC	7	14975	**0.00659**	34277	19302	**0.00578**	40000	25025	**0.00569**	**0.829**	830

Table 10: Setup for the articulated truck combinations simulated with the Schmitz Cargobull trailers

semitrailer	tractor	trailer tires	variation #	empty vehicle vehicle mass [kg]	empty vehicle RRC [-]	average payload (19302kg) vehicle mass [kg]	average payload (19302kg) loading [kg]	average payload (19302kg) RRC [-]	maximum payload vehicle mass [kg]	maximum payload loading [kg]	maximum payload RRC [-]	cd (A=9,5m²) [-]	rotational equivalent mass [kg]
SCB Std	original	low RRC	3	17120	**0.00550**	36422	19302	**0.00487**	40000	22880	**0.00482**	**0.698**	830
SCB Opt	original	high RRC	4	14670	**0.00612**	33972	19302	**0.00568**	38000	23330	**0.00561**	**0.669**	700
SCB Opt	original	low RRC	11	14670	**0.00561**	33972	19302	**0.00485**	38000	23330	**0.00479**	**0.669**	700
SCB Std	high cd	low RRC	8	17120	**0.00550**	36422	19302	**0.00487**	40000	22880	**0.00482**	**0.836**	830
SCB Std	original	high RRC	9	17120	**0.00649**	36422	19302	**0.00575**	40000	22880	**0.00569**	**0.698**	830
SCB Std	high cd	high RRC	10	17120	**0.00649**	36422	19302	**0.00575**	40000	22880	**0.00569**	**0.836**	830

The RRC values found at the test track in Klettwitz seem to be rather high—tests at Papenburg in the DG CLIMA project showed approximately 20% lower RRC values. Furthermore, the tires were rather new and thus had above average RRC values. This may lead to an overestimation of the real world fuel consumption of the tested tractor-trailer combinations. For comparison of different measures to reduce the fuel consumption the effect of an overestimation of the RRC values is rather low, so it was decided not to adapt the RRC values since no other sources for real world RRC values of these tire models are available yet.

The results for the Krone trailers are shown in **Table 11** and **Table 12**. In urban and rural driving the higher vehicle weight of the optimized trailer outweighs the benefits gained by the reduced aerodynamic drag. This increases the fuel consumption by approximately 0.5%. In the simulation with maximum payload no disadvantage in the weight exists in terms of [l/100km]. If the result is related to the payload, the higher vehicle mass proves to be a disadvantage due to the reduced payload.

The trailer tires with the high RRC value increase the fuel consumption by approximately 3% for the empty vehicle and by approximately 4% for the fully loaded vehicle. Due to the increasing share of rolling resistance on the total drag with increasing load, this effect is logical. The (already standard) aerodynamic measures on the tractor reduce the fuel consumption in urban and rural driving by approximately 4%.

Table 11: Results for the **Krone** trailers in the "**urban& rural**" part of the test cycle

mix urban rural								
			empty vehicle		average payload (19302kg)		maximum payload	
semitrailer	tractor	trailer tires	l/100km	g/km	l/100km	g/t-km	l/100km	g/t-km
Krone Std	original	low RRC	**26.6**	**221**	**41.8**	**18.0**	**46.8**	**15.5**
Krone Opt	original	low RRC	26.7	222	41.9	18.0	46.6	15.8
Krone Std	high cd	low RRC	27.7	230	42.8	18.4	47.8	15.9
Krone Std	original	high RRC	27.3	227	43.2	18.6	48.5	16.1
Krone Std	high cd	high RRC	28.4	236	44.3	19.0	49.5	16.4

Index: Value in Line 1 = 100% for urban and rural								
			empty vehicle		average payload (19302kg)		maximum payload	
semitrailer	tractor	trailer tires	l/100km	g/km	l/100km	g/t-km	l/100km	g/t-km
Krone Std	original	low RRC	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Krone Opt	original	low RRC	100.5%	100.5%	100.4%	100.4%	99.6%	101.6%
Krone Std	high cd	low RRC	103.9%	103.9%	102.4%	102.4%	102.1%	102.1%
Krone Std	original	high RRC	102.8%	102.8%	103.4%	103.4%	103.6%	103.6%
Krone Std	high cd	high RRC	106.7%	106.7%	106.0%	106.0%	105.8%	105.8%

During highway driving the aerodynamic drag has higher share of the total driving resistance. Thus, the effect of aerodynamic measures is more beneficial than in urban driving conditions. The optimized Krone trailer reduced the fuel consumption by approximately 1%. Only the value for the fully loaded vehicle (in per ton-km) shows no benefit against the standard trailer due to the reduced payload capacity. The tractor without aerodynamic devices has 6% (fully loaded vehicle) to 10% (empty vehicle) higher fuel consumption compared to the standard tractor design. The influence of the trailer tires with the higher RRC is +3% to +5%, again increasing with increasing vehicle weight.

Table 12: results for the **Krone** trailers in the "**motorway**" part of the test cycle

motorway								
			empty vehicle		average payload (19302kg)		maximum payload	
semitrailer	tractor	trailer tires	l/100km	g/km	l/100km	g/t-km	l/100km	g/t-km
Krone Std	original	low RRC	24.0	199	33.4	14.4	36.3	12.0
Krone Opt	original	low RRC	23.7	197	33.1	14.2	35.8	12.1
Krone Std	high cd	low RRC	26.6	221	35.6	15.3	38.5	12.8
Krone Std	original	high RRC	24.8	206	34.9	15.0	38.0	12.6
Krone Std	high cd	high RRC	27.4	228	37.1	16.0	40.3	13.4

Index: Value in Line 1 = 100% for motorway								
			empty vehicle		average payload (19302kg)		maximum payload	
semitrailer	tractor	trailer tires	l/100km	g/km	l/100km	g/t-km	l/100km	g/t-km
Krone Std	original	low RRC	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Krone Opt	original	low RRC	98.8%	98.8%	99.1%	99.1%	98.7%	100.7%
Krone Std	high cd	low RRC	110.7%	110.7%	106.6%	106.6%	106.1%	106.1%
Krone Std	original	high RRC	103.1%	103.1%	104.5%	104.5%	104.6%	104.6%
Krone Std	high cd	high RRC	114.1%	114.1%	111.3%	111.3%	110.9%	110.9%

The trends found for the Schmitz Cargobull trailers are slightly different to the trends found for the Krone trailers. Due to the lower weight of the optimized trailer compared to the standard trailer the fuel savings per ton-km in urban and rural driving conditions are between 6% (empty) and 3% (fully loaded). The lower weight of the trailer reduces the mass in all loading conditions and increases the payload in the full load condition. All effects are beneficial for the fuel consumption. If low RRC tires become available for the optimized trailer, the total reduction potential is estimated to increase even further - up to 7% per ton-km.

The influence of the trailer tires and tractor aerodynamics are similar to the results discussed for the Krone trailers above where the low RRC trailer tires reduced the fuel consumption by approximately 3 to 4%.

Table 13: Results for the **Schmitz Cargobull** trailers in the "**urban& rural**" part of the test cycle

mix urban rural								
			empty vehicle		average payload (19302kg)		maximum payload	
semitrailer	tractor	trailer tires	l/100km	g/km	l/100km	g/t-km	l/100km	g/t-km
SCB Std	original	low RRC	28.2	234	43.7	18.8	46.9	17.0
SCB Opt	original	high RRC	26.5	220	42.5	18.3	46.2	16.4
SCB Opt	original	low RRC	26.2	217	41.2	17.7	44.7	15.9
SCB Std	high cd	low RRC	29.3	243	44.7	19.2	47.9	17.4
SCB Std	original	high RRC	29.1	241	45.3	19.5	48.6	17.6
SCB Std	high cd	high RRC	30.1	250	46.2	19.9	49.6	18.0

Index: Value in Line 1 = 100% for urban and rural								
			empty vehicle		average payload (19302kg)		maximum payload	
semitrailer	tractor	trailer tires	l/100km	g/km	l/100km	g/t-km	l/100km	g/t-km
SCB Std	original	low RRC	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**
SCB Opt	original	high RRC	93.9%	93.9%	97.2%	97.2%	98.5%	96.6%
SCB Opt	original	low RRC	92.6%	92.6%	94.2%	94.2%	95.4%	93.5%
SCB Std	high cd	low RRC	103.7%	103.7%	102.3%	102.3%	102.1%	102.1%
SCB Std	original	high RRC	102.9%	102.9%	103.5%	103.5%	103.6%	103.6%
SCB Std	high cd	high RRC	106.7%	106.7%	105.8%	105.8%	105.8%	105.8%

Since a reasonable part of the fuel savings in urban driving was gained from the optimized Schmitz Cargobull trailer due to weight reduction (-5% for fully loaded and -14% for an empty trailer), the reduction potential from the optimized trailer in motorway driving is a bit smaller than in urban driving. Since the reduction in aerodynamic drag is only 4.2% (relative difference of Cd-values) compared to more than 5% weight reduction (relative difference of total vehicle mass) the result is logical. The results for the optimized Schmitz trailer suffer from the poor RRC of the trailer tires since the results are compared against a configuration with low RRC tires. If RRC values like from the "Michelin X Energy Saver" are simulated for the Schmitz optimized trailer, fuel savings in the range of 4% (in l/100km for fully loaded) to 7% (empty) were calculated.

Table 14: Results for the **Schmitz Cargobull** trailers in the "**motorway**" part of the test cycle

motorway								
			empty vehicle		average payload (19302kg)		maximum payload	
semitrailer	tractor	trailer tires	l/100km	g/km	l/100km	g/t-km	l/100km	g/t-km
SCB Std	original	low RRC	25.2	209	34.5	14.8	36.4	13.2
SCB Opt	original	high RRC	23.9	198	34.2	14.7	36.4	12.9
SCB Opt	original	low RRC	23.5	195	32.7	14.1	34.9	12.4
SCB Std	high cd	low RRC	27.6	229	36.8	15.8	38.7	14.0
SCB Std	original	high RRC	26.1	216	36.2	15.6	38.1	13.8
SCB Std	high cd	high RRC	28.6	238	38.4	16.5	40.4	14.7

Index: Value in Line 1 = 100% for motorway								
			empty vehicle		average payload (19302kg)		maximum payload	
semitrailer	**tractor**	**trailer tires**	l/100km	g/km	l/100km	g/t-km	l/100km	g/t-km
SCB Std	original	low RRC	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**
SCB Opt	original	high RRC	94.8%	94.8%	99.0%	99.0%	99.9%	97.9%
SCB Opt	original	low RRC	93.3%	93.3%	94.7%	94.7%	95.7%	93.9%
SCB Std	high cd	low RRC	109.4%	109.4%	106.6%	106.6%	106.1%	106.1%
SCB Std	original	high RRC	103.5%	103.5%	104.8%	104.8%	104.7%	104.7%
SCB Std	high cd	high RRC	113.5%	113.5%	111.2%	111.2%	110.9%	110.9%

The explanations of the effects of variations of the Cd values, weight and the RRC values are based on the shares of the different driving resistances over the test cycle computed by PHEM. The sum of driving resistances has to be provided by the positive engine work. **Figure 16** shows the results for the average loaded variants over the total test cycle. The tables with all of the results are provided in the annex. From these tables the effects of weight and RRC on the rolling resistance and the differences in the Cd value on the air resistance can be directly compared for the different variants of tractor-trailer tire combinations. The differences in the cycle work are already close to the differences in fuel consumption since the engine efficiency, on average, does not change significantly due to the small changes in the engine load.

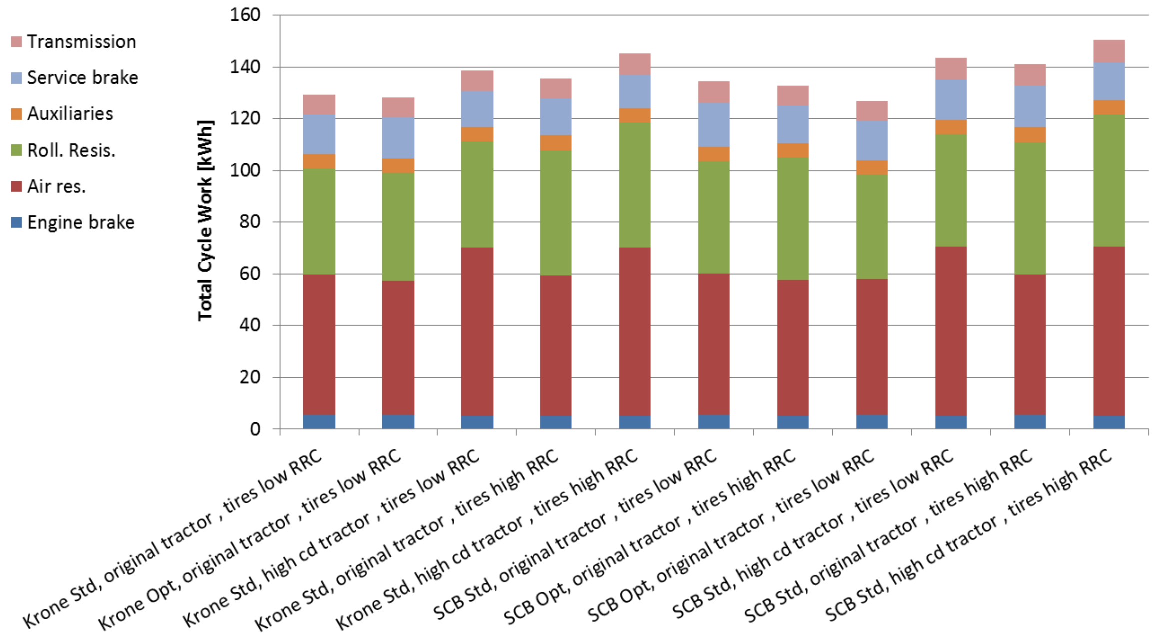

Figure 16: Cycle work computed for the different tractor-trailer combinations with average loading over the entire test cycle (89% motorway, 11% other roads, acceleration work and road gradient work not plotted here)

Comparing the 2.55m wide curtain-sider with the 2.60m refrigeration trailer (curb weight approximately 2.2t higher) shows that the curtain-sider has lower fuel consumption values in all simulated driving conditions. This is a result of the lower weight of this trailer type and also due to the slightly lower frontal area (-2% A-value for the curtain sider). However, the Cd value of curtain siders is known to depend very much on the tension of the curtains. A lower tension most likely would result in a worse Cd value compared to a hard box.

Figure 17 summarizes the fuel consumption simulated for the average loaded tractor-trailer combinations according to the fuel saving technologies applied. The fuel consumption is shown for 89% highway driving and 11% urban and rural driving. Where Krone and Schmitz-Cargobull used the same technology, the fuel consumption shown is the average of the two manufacturers.

If the standard tractor in combination with a standard trailer and high RRC trailer tires is defined as baseline, low rolling resistance tires provide approximately 4.5% in fuel consumption benefit per ton-km. Low rolling resistance tires and aerodynamic measures on the trailer (including a reduction of the trailer weight of 500kg) reduce the fuel consumption by 6.5%. If the weight is additionally reduced (here a reduction potential of 800 kg on the curb weight is assumed) an 8% total reduction against the baseline can be achieved. Based on discussions and the literature, there was a higher expectation for fuel reduction potential prior to this project. Perhaps the baseline was set differently in other studies. If the setup without aerodynamic measures on the tractor is defined as baseline, a reduction in fuel consumption of 13% due to existing technology is computed. Tractors without aerodynamic optimization are not standard in Europe, thus such a baseline seems to be misleading.

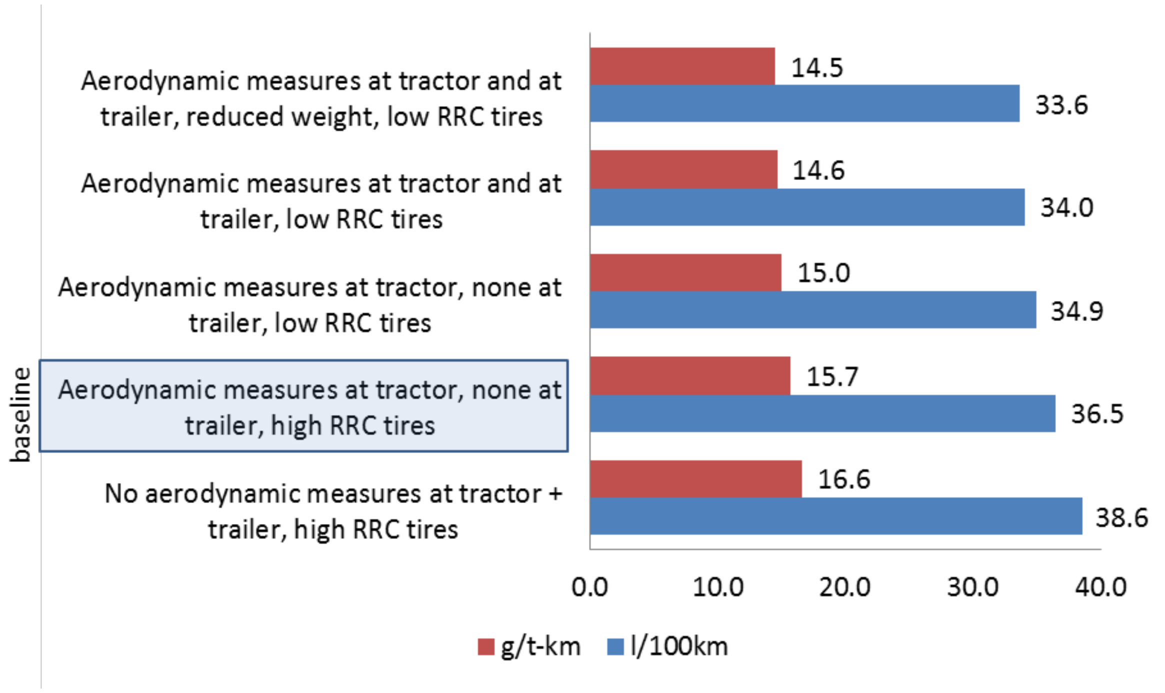

Figure 17: Fuel consumption simulated for the average loaded tractor-trailer combinations summarized according to fuel saving technologies applied

4. LITERATURE

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5. ANNEX

5.1. Technical specifications of the tested semitrailers

Below the main technical specifications of the tested semitrailers are listed. All data are given as delivered by the trailer manufacturers.

5.1.1 Krone trailers

5.1.1.1 3-axle curtainsider (standard aerodynamic)

Type: „SDP 27 eLB4-CS Profi Liner“

maximum allowed fifthwheel load for homologation/operation: 12,000 kg
maximum allowed axle load for homologation/operation: 24,000 kg
maximum allowed total weight for homologation/operation: 36,000 kg
maximum manufacturer‘s fifthwheel load: 12,000 kg
maximum manufacturer‘s axle load: 27,000 kg
maximum manufacturer‘s total weight: 39,000 kg
curb weight: 6,545 kg
compatible with tractor according to ISO 1726:
fifthwheel height above ground in unloaded conditions: 1,150 mm

Chassis:
for lenght of loading space 13,620 mm
for width of loading space 2,480 mm

Axles:
3 axles each with 9,000 kg loading capacity
wheelbase 7,630 mm

Tarpframe:
Interior read door height: 2,700 mm
full height unladen ca. ca. 4,000 mm
diagonal twisting in the top

5.1.1.2 3-axle curtainsider (aerodynamic optimized)

Type: „SDP 27 eLB4-CS Profi Liner“

maximum allowed fifthwheel load for homologation/operation: 12,000 kg
maximum allowed axle load for homologation/operation: 24,000 kg
maximum allowed total weight for homologation/operation: 36,000 kg
maximum manufacturer‘s fifthwheel load: 12,000 kg
maximum manufacturer‘s axle load: 27,000 kg
maximum manufacturer‘s total weight: 39,000 kg
curb weight: 7,100 kg
compatible with tractor according to ISO 1726:
fifthwheel height above ground in unloaded conditions: 1,150 mm

Chassis:
for lenght of loading space 13,620 mm
for width of loading space 2,480 mm
Fuel Saver – wheel covers

Axles:
3 axles each with 9,000 kg loading capacity
wheelbase 7,630 mm
load-dependent fully automatic lift axle control for first axle
manual control for forced lifting (=starting-traction wheel attachment according to Directive 97/27/EG) and forced lowering
Dampers in PDC-construction

Tarpframe:
Interior read door height: 2,700 mm
full height unladen ca. 4,000 mm
diagonal twisting in the top

Tarp:
Easy-tarp – side-tarps with pneumatic quick fastener

5.1.2 Schmitz Cargobull trailers

5.1.2.1 3-axle refrigeration box-trailer (standard aerodynamic)

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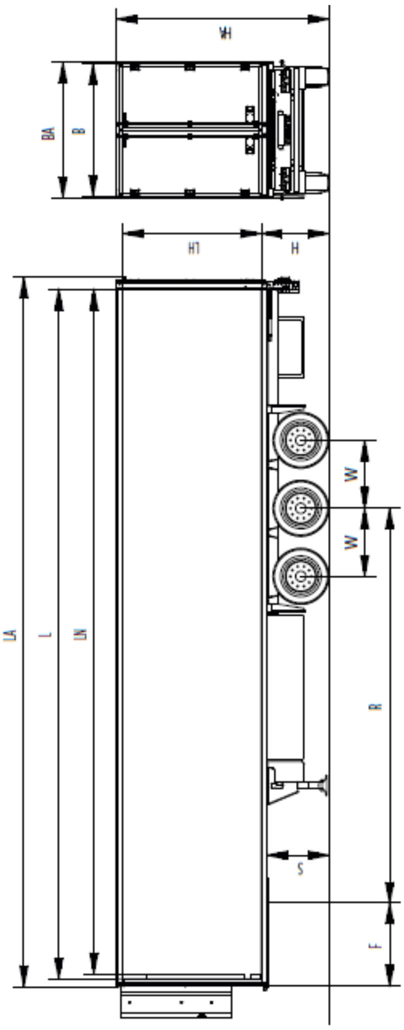
OOL

24/L – 13.4 FP 60



Body length (LA)	approx. 13,600 mm
Interior body length (L)	approx. 13,410 mm
Interior body width (B)	approx. 2,460 mm
Interior body height (LH)	approx. 2,650 mm
Usable body length (LN)	approx. 13,315 mm
Usable body height	approx. 2,650 mm
Full height, unladen (HA)	approx. 4,008 mm
Full height front unladen	approx. 4,009 mm
Full height rear unladen	approx. 4,008 mm
Trailer coupling height, rear, unladen (H)	approx. 1,273 mm
Tyres 4 x	385/65 R 22.5"
Total weight	39,000 kg
Payload	31,040 kg
Axle unit load	27,000 kg
Fifthwheel load	15,000 kg
Unladen weight	+/- 3 % 7,960 kg
Trailer coupling height, unladen (S)	approx. 1,140 mm
Trailer coupling height, loaded (S)	approx. 1,115 mm
Total length	approx. 13,550 mm
Riding height	410 mm
Body width (BA)	overall approx. 2,600 mm
Wheelbase (R)	7,600 mm
Interior rear door height	approx. 2,640 mm
Interior rear door width	approx. 2,460 mm
Axle distance (W)	1.310 mm
Front overhang (F)	1.600 mm

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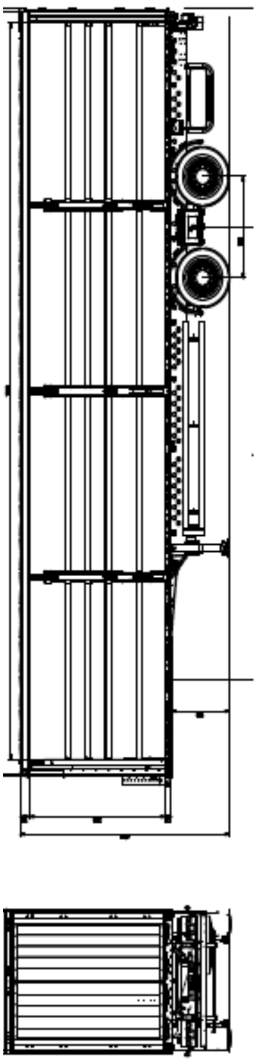
2010

5.1.2.2 2-axle box-trailer (aerodynamic optimized)

Datasheet refers to a curtainsider variant but dimensions also match with the box-trailer.



Axles	2 x 10,000 kg
Track / spring centre	2,040 / 1,300 mm
Disc brakes	Ø 370 mm
Axle spacing	1,810 mm
Tyres	385/65 R 22.5" (LI 164)
Trailer load	12,000 kg
Aggregate load (technical)	20,000 kg
Gross vehicle weight (technical)	32,000 kg
Unladen weight*	5,230 kg
Payload (technical)	26,770 kg
Overall length	13,720 mm
Overall width	2,550 mm
Internal body length	13,620 mm
Internal body width	2,480 mm
Side through-loading length	13,090 mm
Internal body height front / rear	2,860 / 2,860 mm
Side through-loading height front / rear	2,600 / 2,600 mm
Frame height front / rear	125 / 396 + 27 mm
Fifth wheel height (loaded**)	1,125 mm
Rear loading height (loaded)	1,249 mm
Overall height when laden, approx.	4,000 mm

5.2. Driving resistances computed

semitrailer	tractor	tires	variation #	mix urban rural																										
				empty vehicle									average payload (19302kg)									gross vehicle weight								
				EposICE [kWh]	EnegICE [kWh]	Eair [kWh]	Eroll [kWh]	Egrad [kWh]	Eacc [kWh]	Eaux [kWh]	Ebrake [kWh]	Etransm [kWh]	EposICE [kWh]	EnegICE [kWh]	Eair [kWh]	Eroll [kWh]	Egrad [kWh]	Eacc [kWh]	Eaux [kWh]	Ebrake [kWh]	Etransm [kWh]	EposICE [kWh]	EnegICE [kWh]	Eair [kWh]	Eroll [kWh]	Egrad [kWh]	Eacc [kWh]	Eaux [kWh]	Ebrake [kWh]	Etransm [kWh]
Krone Std	original	low RRC	1	11.82	-0.99	-3.17	-2.65	0.00	-1.17	-1.68	-1.35	-0.82	20.42	-1.54	-3.17	-5.32	0.00	-2.27	-1.68	-4.75	-1.70	23.10	-1.60	-3.17	-6.11	0.00	-2.68	-1.68	-5.90	-1.97
Krone Opt	original	low RRC	2	11.91	-1.03	-3.03	-2.71	0.00	-1.20	-1.68	-1.43	-0.84	20.53	-1.55	-3.03	-5.38	0.00	-2.29	-1.68	-4.88	-1.72	23.00	-1.61	-3.03	-6.11	0.00	-2.68	-1.68	-5.93	-1.96
Krone Std	high cd	low RRC	5	12.39	-0.93	-3.80	-2.65	0.00	-1.17	-1.68	-1.32	-0.85	20.92	-1.51	-3.80	-5.32	0.00	-2.27	-1.68	-4.64	-1.72	23.59	-1.57	-3.80	-6.11	0.00	-2.68	-1.68	-5.77	-1.99
Krone Std	original	high RRC	6	12.22	-0.94	-3.17	-3.12	0.00	-1.17	-1.68	-1.31	-0.84	21.15	-1.49	-3.17	-6.27	0.00	-2.27	-1.68	-4.56	-1.73	23.93	-1.55	-3.17	-7.21	0.00	-2.68	-1.68	-5.65	-2.00
Krone Std	high cd	high RRC	7	12.79	-0.88	-3.80	-3.12	0.00	-1.17	-1.68	-1.28	-0.86	21.76	-1.46	-3.81	-6.28	0.00	-2.33	-1.68	-4.45	-1.76	24.45	-1.52	-3.80	-7.21	0.00	-2.68	-1.68	-5.53	-2.03
SCB Std	original	low RRC	3	12.81	-1.08	-3.20	-2.98	0.00	-1.29	-1.68	-1.66	-0.92	21.51	-1.56	-3.21	-5.62	0.00	-2.46	-1.68	-5.18	-1.81	23.13	-1.60	-3.20	-6.11	0.00	-2.68	-1.68	-5.90	-1.97
SCB Opt	original	high RRC	4	11.76	-0.95	-3.07	-2.84	0.00	-1.14	-1.68	-1.27	-0.81	20.80	-1.49	-3.07	-6.11	0.00	-2.24	-1.68	-4.51	-1.70	22.77	-1.54	-3.07	-6.76	0.00	-2.54	-1.68	-5.28	-1.89
SCB Opt	original	low RRC	11	11.56	-0.98	-3.07	-2.60	0.00	-1.14	-1.68	-1.29	-0.80	20.11	-1.54	-3.07	-5.21	0.00	-2.24	-1.68	-4.70	-1.68	22.02	-1.59	-3.07	-5.77	0.00	-2.54	-1.68	-5.51	-1.87
SCB Std	high cd	low RRC	8	13.36	-1.03	-3.83	-2.98	0.00	-1.29	-1.68	-1.62	-0.94	22.01	-1.53	-3.84	-5.62	0.00	-2.46	-1.68	-5.05	-1.82	23.62	-1.57	-3.83	-6.11	0.00	-2.68	-1.68	-5.77	-1.99
SCB Std	original	high RRC	9	13.25	-1.03	-3.20	-3.52	0.00	-1.29	-1.68	-1.60	-0.93	22.29	-1.51	-3.21	-6.64	0.00	-2.46	-1.68	-4.96	-1.83	23.96	-1.55	-3.20	-7.21	0.00	-2.68	-1.68	-5.65	-2.00
SCB Std	high cd	high RRC	10	13.82	-0.97	-3.83	-3.52	0.00	-1.29	-1.68	-1.57	-0.96	22.79	-1.48	-3.84	-6.64	0.00	-2.46	-1.68	-4.84	-1.85	24.47	-1.52	-3.83	-7.21	0.00	-2.68	-1.68	-5.53	-2.03

semitrailer	tractor	tires	variation #	motorway																										
				empty vehicle									average payload (19302kg)									gross vehicle weight								
				EposICE [kWh]	EnegICE [kWh]	Eair [kWh]	Eroll [kWh]	Egrad [kWh]	Eacc [kWh]	Eaux [kWh]	Ebrake [kWh]	Etransm [kWh]	EposICE [kWh]	EnegICE [kWh]	Eair [kWh]	Eroll [kWh]	Egrad [kWh]	Eacc [kWh]	Eaux [kWh]	Ebrake [kWh]	Etransm [kWh]	EposICE [kWh]	EnegICE [kWh]	Eair [kWh]	Eroll [kWh]	Egrad [kWh]	Eacc [kWh]	Eaux [kWh]	Ebrake [kWh]	Etransm [kWh]
Krone Std	original	low RRC	1	98.73	-2.59	-62.18	-22.63	0.05	1.31	-6.06	-1.71	-4.92	140.09	-5.81	-60.55	-45.40	0.12	2.78	-6.22	-16.67	-8.39	152.89	-6.22	-60.07	-52.12	0.15	3.21	-6.27	-22.15	-9.46
Krone Opt	original	low RRC	2	97.21	-3.03	-59.48	-23.17	0.05	1.36	-6.06	-1.99	-4.88	138.93	-5.92	-57.89	-45.97	0.14	2.82	-6.22	-17.54	-8.40	150.67	-6.31	-57.48	-52.11	0.09	3.30	-6.26	-22.56	-9.38
Krone Std	high cd	low RRC	5	110.57	-1.74	-74.60	-22.63	0.05	1.31	-6.06	-1.48	-5.42	150.51	-5.60	-72.54	-45.40	0.07	2.87	-6.22	-14.92	-8.81	162.94	-5.85	-71.93	-52.12	0.11	3.26	-6.27	-20.34	-9.84
Krone Std	original	high RRC	6	102.48	-2.24	-62.18	-26.68	0.05	1.31	-6.06	-1.60	-5.08	147.11	-5.67	-60.46	-53.55	0.16	2.78	-6.22	-15.48	-8.68	160.76	-5.92	-59.97	-61.52	0.21	3.16	-6.27	-20.74	-9.76
Krone Std	high cd	high RRC	7	114.50	-1.50	-74.60	-26.68	0.05	1.31	-6.06	-1.43	-5.60	157.69	-5.48	-72.49	-53.56	0.08	2.82	-6.23	-13.77	-9.11	171.01	-5.70	-71.78	-61.52	0.25	3.11	-6.28	-18.94	-10.17
SCB Std	original	low RRC	3	104.03	-3.37	-62.81	-25.45	0.06	1.49	-6.06	-2.61	-5.27	145.44	-5.94	-60.97	-47.95	0.06	3.00	-6.24	-18.61	-8.81	153.35	-6.20	-60.66	-52.11	0.20	3.19	-6.27	-22.06	-9.47
SCB Opt	original	high RRC	4	98.10	-2.43	-60.20	-24.27	0.05	1.28	-6.06	-1.60	-4.87	143.83	-5.71	-58.59	-52.15	0.13	2.81	-6.22	-15.61	-8.51	153.41	-5.88	-58.23	-57.62	0.22	2.95	-6.26	-19.32	-9.29
SCB Opt	original	low RRC	11	96.23	-2.60	-60.20	-22.25	0.05	1.28	-6.06	-1.65	-4.79	137.35	-5.85	-58.67	-44.54	0.15	2.72	-6.21	-16.73	-8.26	146.28	-6.16	-58.29	-49.20	0.23	2.95	-6.25	-20.58	-9.00
SCB Std	high cd	low RRC	8	115.57	-2.57	-75.23	-25.45	0.06	1.49	-6.06	-2.03	-5.77	155.73	-5.69	-72.90	-47.95	0.18	2.88	-6.24	-16.84	-9.22	163.44	-5.84	-72.54	-52.12	0.16	3.23	-6.27	-20.24	-9.86
SCB Std	original	high RRC	9	108.26	-3.09	-62.81	-30.03	0.06	1.49	-6.06	-2.36	-5.45	152.80	-5.74	-60.88	-56.61	0.18	2.90	-6.24	-17.34	-9.10	161.34	-5.90	-60.58	-61.53	0.15	3.20	-6.27	-20.65	-9.79
SCB Std	high cd	high RRC	10	119.88	-2.24	-75.23	-30.03	0.06	1.49	-6.06	-1.91	-5.95	163.20	-5.55	-72.78	-56.60	0.18	2.90	-6.25	-15.60	-9.53	171.59	-5.69	-72.39	-61.53	0.08	3.25	-6.28	-18.86	-10.19

5.3. Background information

This section gives additional background information on measurement and data evaluation methods. The shown figures have been presented at the meeting with VDA and truck and trailer manufacturers in Munich in November 2011.

Figure 18 summarizes the single steps in the data evaluation as performed for the constant speed tests and gives an example how the road load curve is determined from the single data points for sum of driving resistance (rolling and air resistance) as a function of air inflow speed in driving direction.

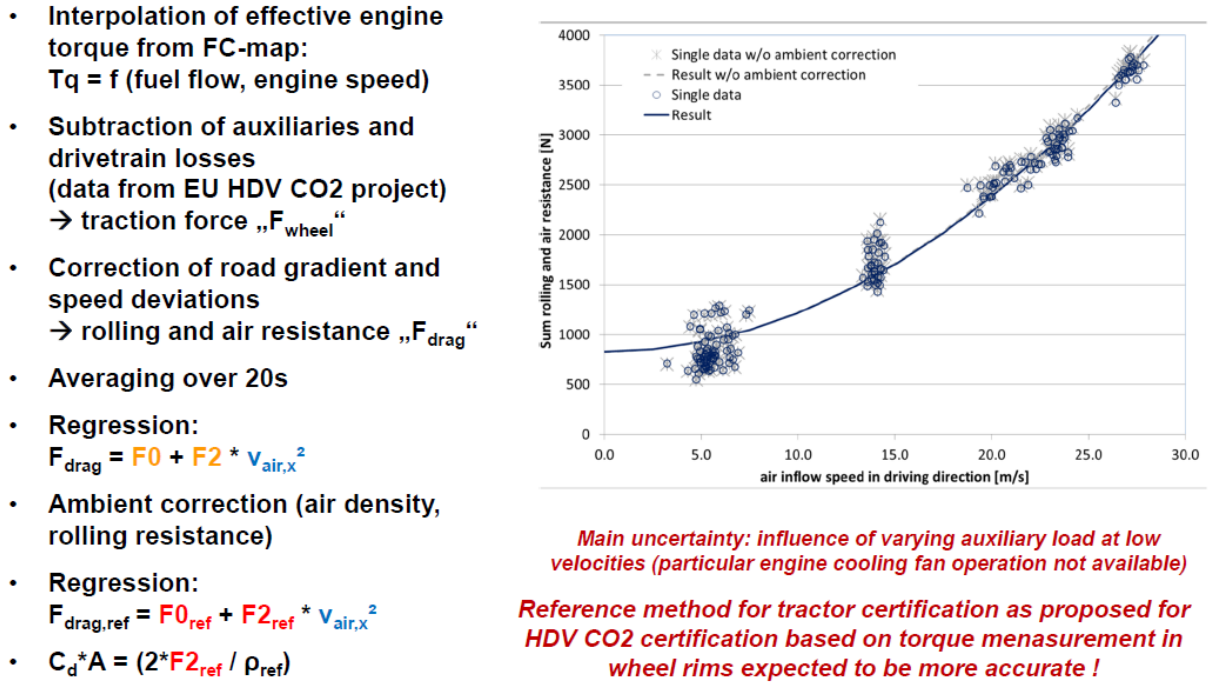


Figure 18: Data analysis – constant speed tests

Figure 19 gives an overview on evaluation methods for the coast down tests and shows and an chart with an example dataset.

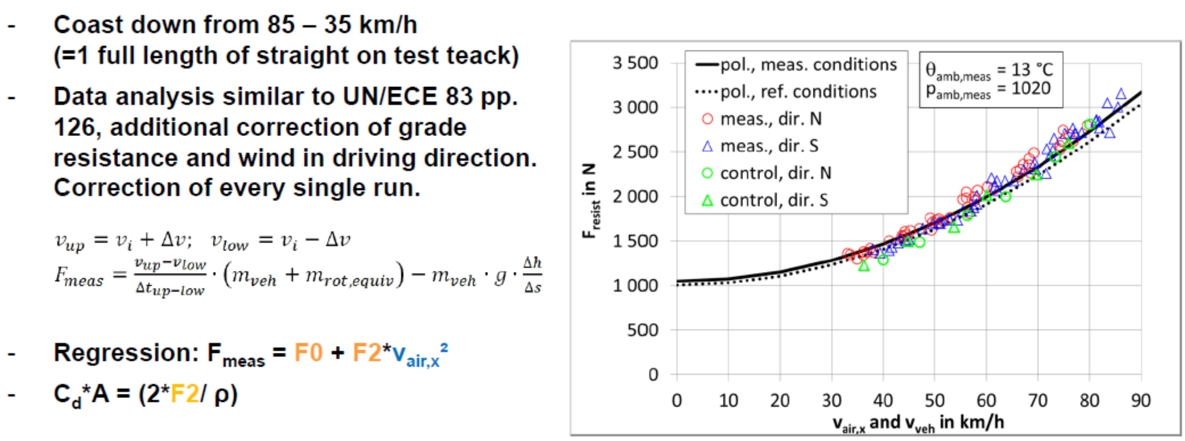


Figure 19: Data analysis – coast down tests

Figure 20 to **Figure 23** give a comparison of the road load curves derived from constant speed and from coast down tests for the four tested semitrailers. Only measurements in comparable ambient conditions (no rain or heavy wind) are shown in the pictures. The labeling of the curves matches with the test matrix as shown in Table 3 on page 12. Figure 20 additionally indicates the speed range covered by the two different test procedures.

As a general trend the road load curves from coast down tests result in higher values at low speeds (=rolling resistance) than from the constant speed tests. This effect is not fully understood yet but might be mainly attributed to the following effects:

- The coasts down tests as performed in this project do not cover the low vehicle speed range. As a consequence in the coast down evaluation the rolling resistance has to be extrapolated from the gradient of the road load curve in the high speed range. On the other hand covering low vehicle speeds by coast down tests has the disadvantages that a either very long test track straight is needed or the coast downs have to be split into two velocity ranges and that the repeatability of test results significantly decreases due to general problems measuring low accelerations levels which occur at low vehicle speeds.
- In the road load curves determined from coast down tests unknown transmission idling losses are included which to some extend falsify the test results for rolling and air resistance.

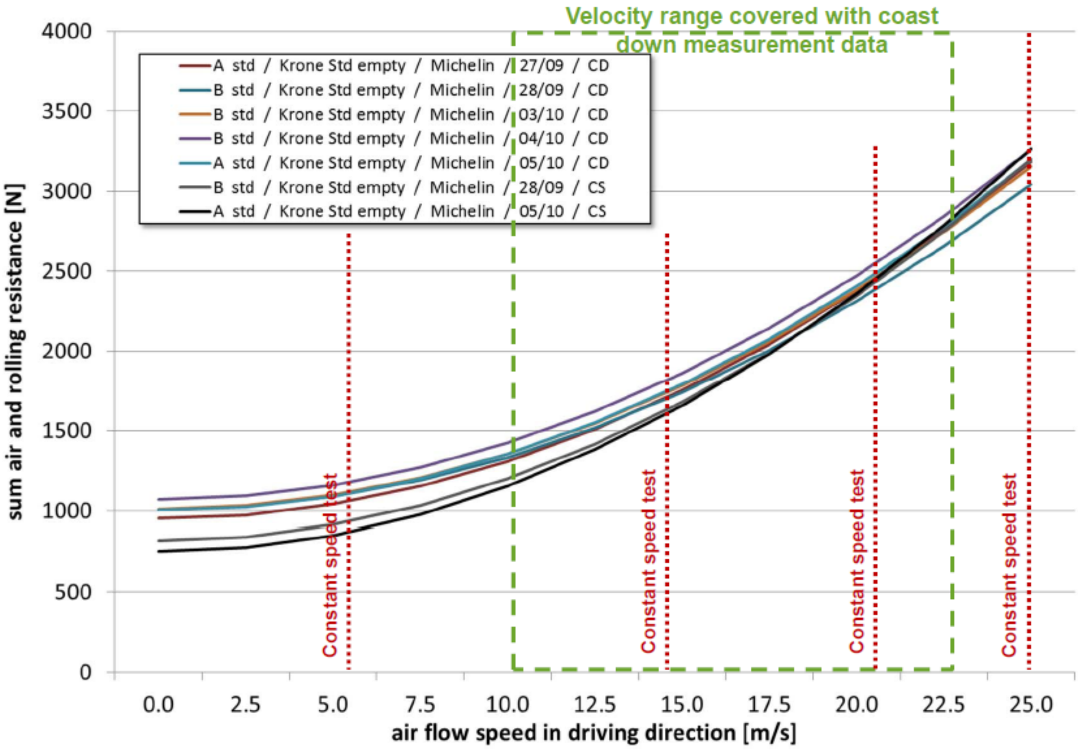


Figure 20: Comparison road load curves derived from constant speed and from coast down tests – Krone 3-axle curtainsider standard aerodynamics

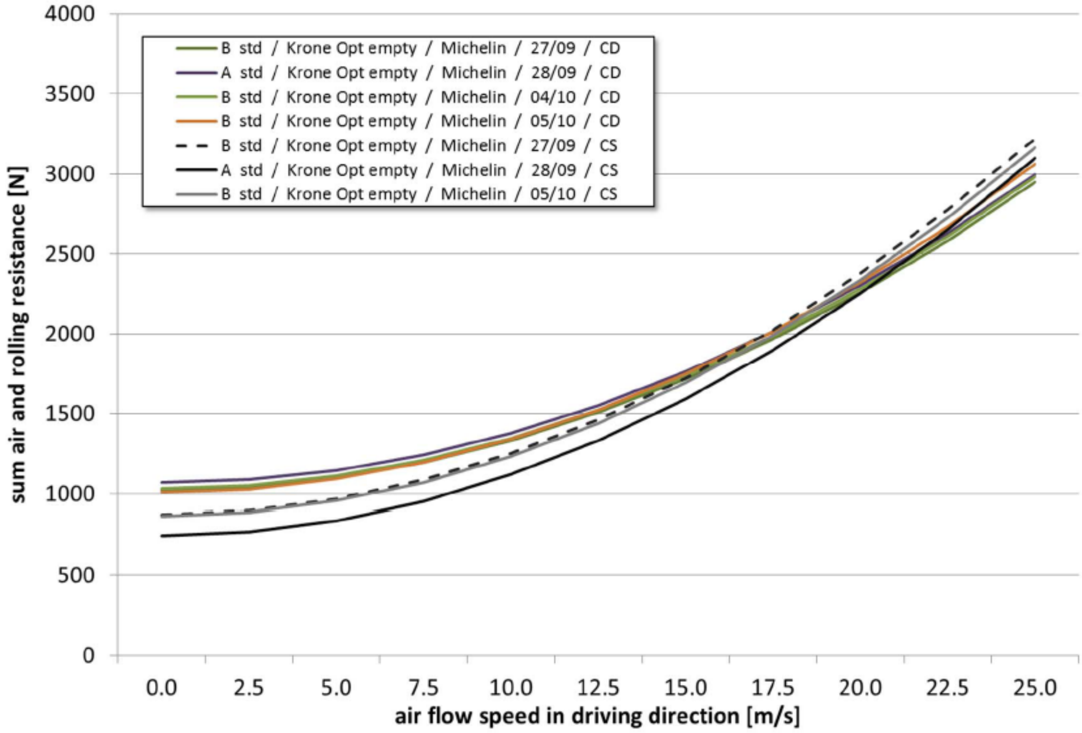


Figure 21: Comparison road load curves derived from constant speed and from coast down tests – Krone 3-axle curtainsider optimized aerodynamics

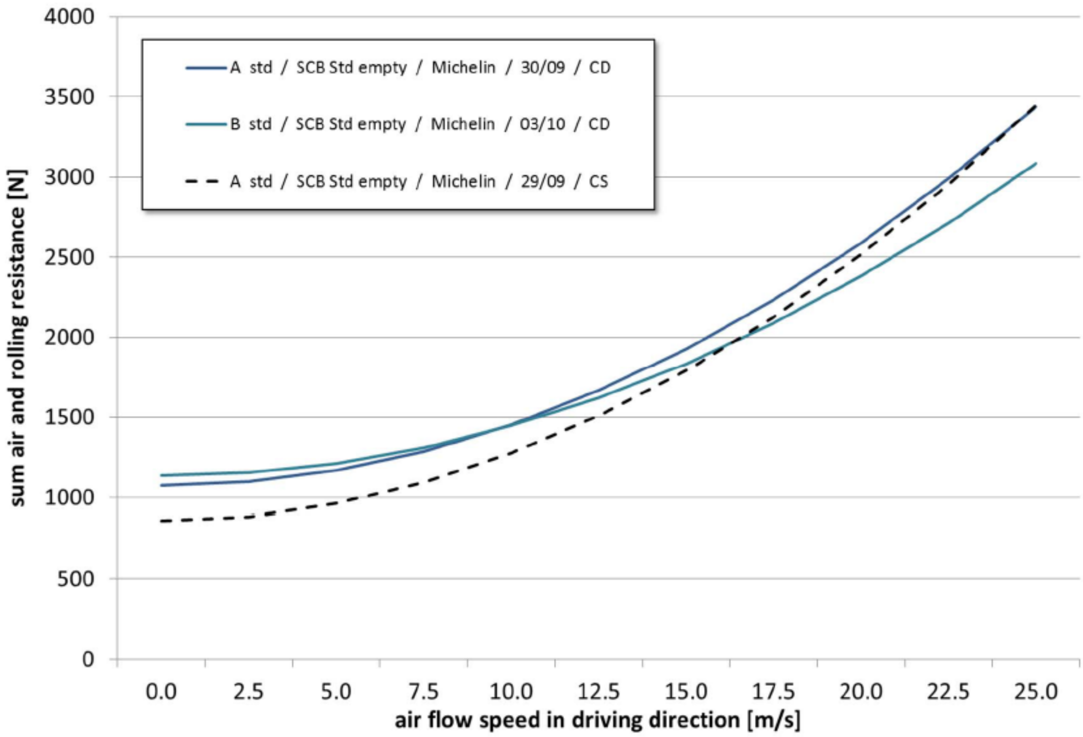


Figure 22: Comparison road load curves derived from constant speed and from coast down tests – Schmitz Cargobull 3-axle refrigeration box-trailer (standard aerodynamics)

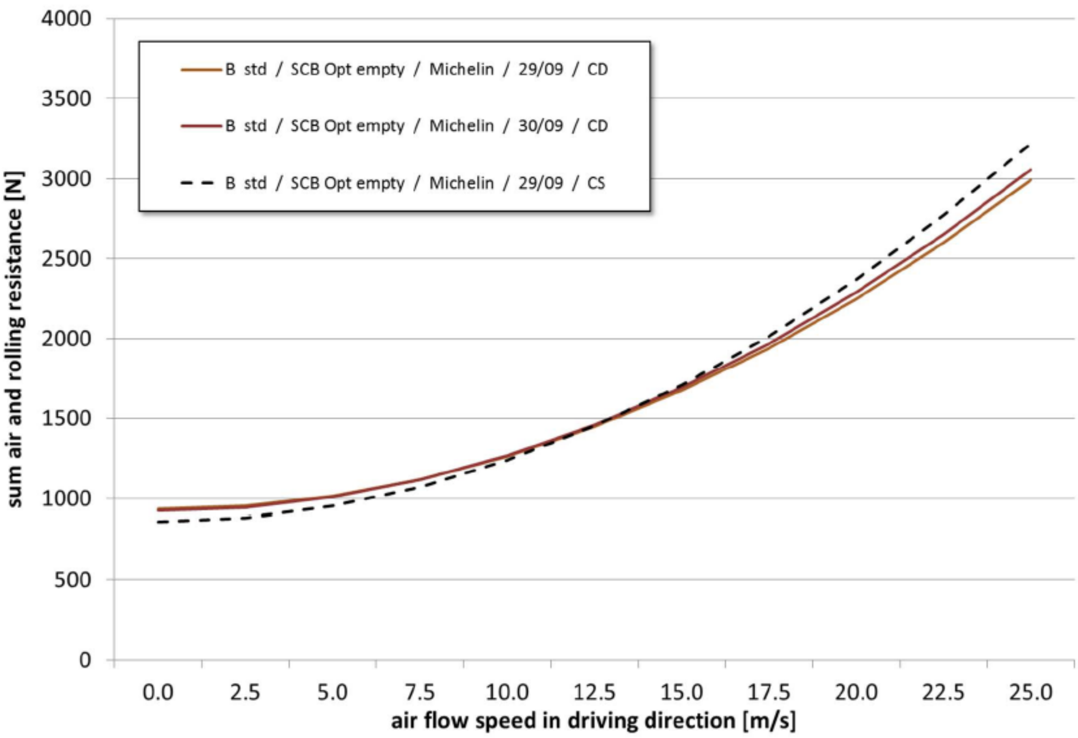


Figure 23: Comparison road load curves derived from constant speed and from coast down tests – Schmitz Cargobull 2-axle box-trailer (optimized aerodynamics)