RESEARCH REPORT

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Driving Resistance Measurements of Heavy-Duty Vehicles

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beyond the obvious

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Driving Resistance Measurements of Heavy-Duty Vehicles	
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Summary

Heavy duty vehicles is a versatile group with a variety of component options and technical details, which are chosen for their specific transport mission, and which are affecting their driving resistances. Aerodynamic resistance and tire rolling resistance are external resistive forces acting on the vehicle, which make up the main share of the vehicle energy consumption on highway driving. Aerodynamics depend on the vehicle configuration, dimensions and the bodywork, which may have the maximized volume with a box body shape or some special shape and structure for certain cargos. Tires may have different configurations, sizes, and tread patterns for different axle position in the vehicle and for different use cases.

In this project, aerodynamic resistance and tire rolling resistance values are measured for typical Finnish heavy vehicle combinations. These values are used in further studies of vehicle energy usage for different heavy vehicle types and bodyworks.

Five different heavy-duty vehicle combinations were measured using a coast-down test to get reference values for total resistive forces acting on the vehicle. All vehicle combinations were approved for operation with 76 tonnes gross vehicle weight. Two vehicles had bulk bodies, one gravel/tipper body, and one timber body. Aerodynamic resistance force was estimated based on earlier measurements of driveline losses.

Also, rolling resistance values of typical trailer tires were measured in laboratory conditions on a chassis dynamometer to give insight to rolling resistance values as a function of driving speed, tire load and tire temperature.

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Contents

1. Introduction

External forces resisting vehicle motion are aerodynamic force, tire rolling resistance, and hill climbing force. For heavy vehicle combinations, the aerodynamic resistance and tire rolling resistance make up most of the power requirement on highway driving speeds and take a major share of the total energy consumption. Heavy vehicles tailored for specific transport missions with different vehicle configurations, body works, tires and driveline types have an effect on the driving resistance values. Information on the driving resistance values is important, when analysing the energy consumption of heavy-duty vehicles using computer simulations and finding more efficient transport solutions.

In this work, five different types of vehicle combinations with the maximum allowed mass of 76 tonnes were studied to define their driving resistances. These driving resistance values can be used as reference values for typical Finnish vehicle combinations, and these values complement the information gathered for heavy duty vehicles in previous studies [1][2]. Furthermore, tire rolling resistance values for typical trailer tire setups are measured under laboratory conditions. These values give insight on the effect of main operation parameters on the rolling resistance value.

This work was performed by VTT Technical Research Centre during summer and autumn of 2023 and spring of 2024 in a project called *Net-effect optimized data and modeling assisted green and efficient truck* (NO DAMAGE) funded by Business Finland.

2. Goal

The goal of the work is to give accurate reference data of driving resistance values, tire rolling resistance and aerodynamic drag, for heavy vehicle combinations. Work includes on-road measurements with vehicle combinations and laboratory measurements for heavy vehicle tires.

Driving resistance forces acting on the vehicle are measured using coast-down tests for five heavy vehicle combinations with different body works:

- Bulk body 1: 8x4*4 truck with 5-axle trailer
- Bulk body 2: 6x4 truck with 6-axle trailer
- Swap body: 8x4*4 truck with 5-axle trailer
- Tipper/cassette body: 10x4*4 truck with 4-axle trailer
- Timber body: 8x4*4 truck with 5-axle trailer

In laboratory, tire rolling resistance as a function of driving speed are measured for four different free rolling tire sets using a chassis dynamometer:

- Twin tires: 275/70R22.5 265/70R19.5
- Single tires: 385/55R22.5 445/45R19.5

Tire rolling resistance is measured with axle loads of 4 tonnes and 7 tonnes using the same tire pressure value of 8.5 bar at the beginning of the tests. Also, the effects of decreased tire pressures are measured for each tire set.

3. Methods

Tested vehicles and tires, test procedures, and data processing are described in the following. Driving resistances of heavy vehicles were measured on-road with coast-down test to define the total resistive force acting on the vehicle. Tire rolling resistance values were measured in laboratory using a chassis dynamometer and its coast-down measurement program.

3.1 Coast-Down Measurements

In the coast-down test, the vehicle is accelerated to a constant speed, in this case 80 km/h, and then allowed to slow down with neutral gear until it stops. The vehicle is equipped with a measurement system to record the vehicle speed, location, and wind speed and direction encountered by the vehicle. Using the recorded data, the mass of the vehicle, and the information of the slope encountered by the vehicle, the resistive forces acting on the vehicle can be defined.

In the data processing, the vehicle motion during the coast-down is simulated and compared against the measured vehicle motion. In the simulation, the equation for the vehicle motion is

$$(m + m_{rot})\frac{dv}{dt} = -mgc_0 - c_1 v - c_2 v^2 - mg\alpha \qquad (1)$$

where m is the mass of the vehicle, m_{rot} is the rotational mass, v driving speed, t time, g gravity 9,81 m/s^2, and α slope. Resistance force acting on the vehicle is assumed to be second order polynomial as a function of vehicle speed with coefficients c_0, c_1 ja c_2, where c_0 presents rolling resistance coefficient, c_1 speed coefficient, and c_2 presents aerodynamic drag with an equation

$$c_2 = \frac{1}{2}\rho C_D A \qquad (2)$$

where ρ is the air density, C_D is the drag coefficient, and A is the frontal area. In the results, the air drag coefficient and frontal area are combined to one coefficient $C_D A$.

During the data processing, an optimization process is used to find the driving resistance coefficients in such a way that the RMS error between measured and simulated values is minimized. Figure 1 shows an example of measured speed and distance values as a function of time, and simulated values using resistance coefficients given by the data processing routine.

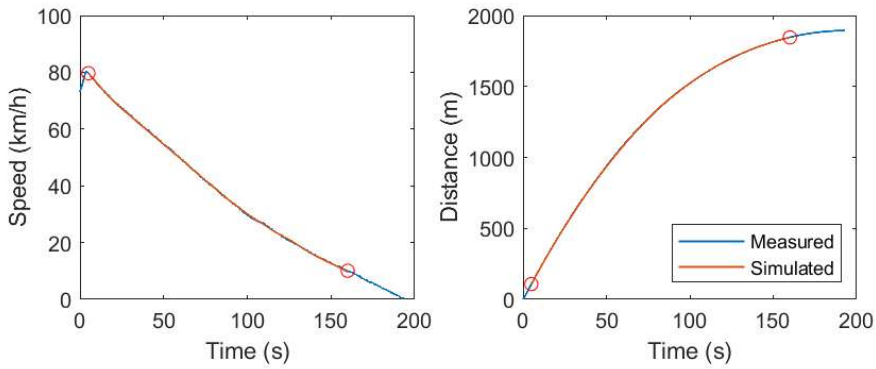

Figure 1. Measured and simulated vehicle speed and distance as a function of time during a coast-down test.

For each vehicle, the rotational mass is estimated based on the number of axles, tires, and driveline configuration to take into account inertia force during coast-down deceleration. Rotational masses are shown in Table 1, and the values are based on previous measurements done on chassis dynamometer at VTT laboratory.

The coast-down measurement defines the total resistive force acting on the vehicle. The data post-processing defines the resistive force using a second order polynomial as a function of driving speed. Total resistance force acting on the vehicle during the coast-down test includes also the internal resistive force of the driveline, which depends on the driveline configuration. Considering the driveline loss force during the data processing would require a measurement of driveline losses of each vehicle, which could not be implemented during the project. In this work, the estimation of driveline losses is done based to the driveline configuration, whether there is a tandem driven bogie with single reduction axles or a tandem driven bogie with hub reduction axles, and representative data from previous measurements. Driveline losses as a function of driving speed without external driveline torque are shown in Figure 2. The measurements of the driveline losses are done with different vehicles and there might be differences in the technical system and final drive ratio, but using this reference data the rolling resistance force and aerodynamic force without driveline loss component can be estimated from the total resistive force.

During the on-road tests, vehicles were equipped with Race Logic DL-1 GPS and accelerometer data logging system accompanied by Vaisala Ultrasonic wind speed and wind direction sensor. Before coast-down tests, vehicles were driven at least for half an hour to warm-up the tires and driveline. Measurements were done unloaded with all liftable axles down. In addition, the timber truck was measured also in loaded condition.

Table 1. Rotational masses for different axle and tire configurations.

Axle component	Mass (kg)
Tandem bogie with single reduction gear	500
Tandem bogie with hub reduction gear	650
Axle with single tires, rim 22.5”	150
Axle with twin tires, rim 22.5”	250
Axle with single tires, rim 19.5”	125
Axle with twin tires, rim 19.5”	240

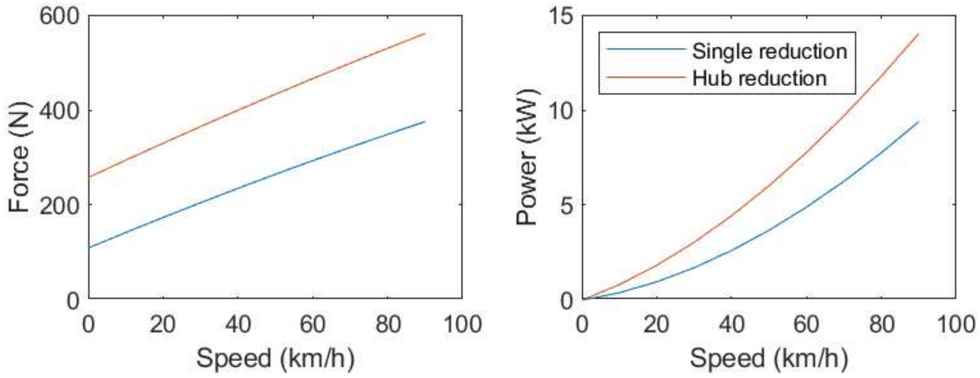

Figure 2. Resistive forces acting on the vehicle of free rolling tandem bogie drivelines with single and hub reduction axles.

Vehicle combinations involved in the coast-down test are shown with their main technical data in Figure 3. Vehicle combinations with bulk and swap bodies came from Korsu Oy while vehicles with timber and gravel bodyworks were borrowed from Volvo Trucks (Volvo Finland Ab).

Volvo FH 540 8x4*4 with single reduction axles

Bulk body

Tires on steerable axles 385/55R22.5 and on driven axles 315/70R22.5

Briab bulk trailer, five axles

Tires (twin) 265/70R19.5

Scania R 540 6x4 with single reduction axles

Bulk body

Tires on steerable axle 385/55R22.5 and on driven axles 315/70R22.5

Briab bulk trailer, six axles

Tires (twin, five axles) 265/70R19.5 and 445/45R19.5 (single, one axle)

Volvo FH 500 8x4*4 with single reduction axles

Hooklift and an uncovered swap body

Tires on steerable axles 385/55R22.5 and on driven axles 315/70R22.5

Briab swap body trailer, five axles, two uncovered swap bodies

Tires (twin) 265/70R19.5

Volvo FMX 540 10x4*4 with hub reduction axles

Tipper/cassette body

Tires on steerable axles 385/65R22.5 and on driven axles 315/80R22.5

Jyki cassette trailer, four axles

Tires (twin) 295/80R22.5

Volvo FH 750 8x4*4 with hub reduction axles

Timber carrying body

Tires on steerable axles 385/65R22.5 and on driven axles 315/80R22.5

Briab timber trailer, five axles

Tires (twin) 265/70R19.5

Figure 3. Vehicle combinations used for the coast-down test measurement.

3.2 Tire Measurements

Tire rolling resistance was measured using a coast-down function of the chassis dynamometer. Before measurement, tire pressure was set to 8.5 bar. Then coast-down test was performed with cold tires three times in a row. After that a warm-up run of roughly one hour was performed. The coast-down test was then repeated with warm tires. The same procedure was performed with axle loads of 4 tonnes and 7 tonnes. For the higher axle load also test with lower tire pressure was performed.

Test rigs used for measurements are shown in Figure 4 and Figure 5.

Figure 4. Dolly test rig used for tires with 22.5” rims.

Figure 5. Trailer test rig used for tires with 19.5” rims.

4. Results

4.1 Driving Resistance Coefficients

Driving resistance coefficients for the five vehicle combinations are presented in Table 2. Values are shown both without the consideration of driveline loss and with the estimated driveline loss. The ambient temperatures during the measurements varied from +5 to +12 °C. Wind conditions have varied, but mostly the wind speed was low. For some tests the road surface has been wet.

*Table 2. Driving resistance coefficients for measured vehicle combinations without and with the estimated driveline resistive force (marked * for single reduction axles and ** for hub reduction axles).*

Vehicle combination	RRC (N/kN)	Air drag C_dA (m^2)
Bulk body 1: 8x4*4 truck and 5-axle trailer	7.5 / 6.7*	9.0 / 8.2*
Bulk body 2: 6x4 truck and 6-axle trailer	6.6 / 5.9*	9.6 / 9.0*
Swap bodies: 8x4*4 truck and 5-axle trailer	6.4 / 5.5*	10.0 / 9.3*
Tipper/cassette body: 10x4*4 truck and 4-axle trailer	7.8 / 6.6**	10.3 / 9.5**
Timber carrying body: 8x4*4 truck and 5-axle trailer	8.9 / 7.4** 6.3 / 5.8**	(unloaded) 15.0 / 14.2** (loaded) 14.2 / 13.5**

The coefficient of driving speed, c_0, is 0.001-0.002 Ns/m for all measured vehicles.

4.2 Tire Rolling Resistance

Tire rolling resistance for the tested tire sets is presented as a function of driving speed. Figure 6 shows rolling resistance force for 385/55R22.5 and 275/70R22.5 tires with 4 tonnes and 7 tonnes axle load, and Figure 7 for 445/45R19.5 and 265/70R19.5 tires respectively. Each plot includes three runs with cold tires (blue curves), which means the tires were at the ambient laboratory room temperature of around +25 °C. During each run the tire gets warmer and the resistance force decreases. After the three cold measurements, tires were warmed for roughly one hour with constant speed of 80 km/h. Instantly after the warm-up session, three coast-down runs were performed with warm tires (red curves). With warm tires the measured resistance forces are close to each other with each run.

For each tire set, the tire pressure is set to the reference value of 8.5 bar before the tests with cold tires. After the coast-downs with cold tires, tire warm-up phase, and coast-downs with warm tires, the tire pressure is in a range of 8.8−9.6 bar, and mostly around 9 bar. The highest pressure increase was measured with 445/45R19.5 tires. For 7 tonnes axle load, rolling resistances with tire pressures decreased 2 bar from the pressure value after the warm measurements are shown in Figure 8.

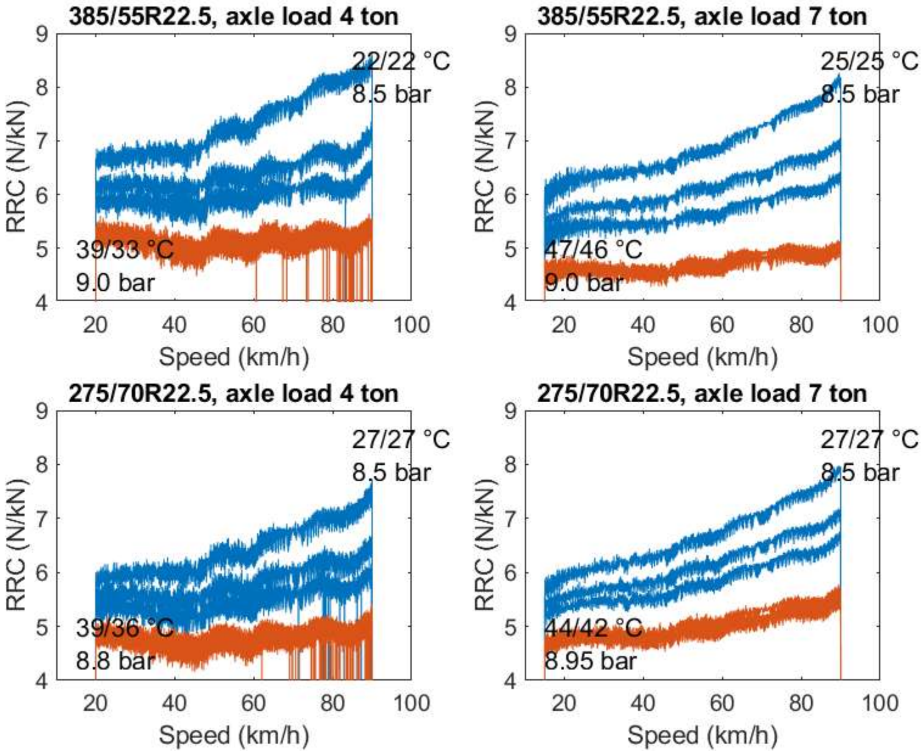

Figure 6. Rolling resistance coefficient of tires 385/55R22.5 and 275/70R22.5 as a function of speed for 4- and 7-tonnes axle load. Measurement with cold tires (blue curves) and with warm tires (red curves). Initial and final temperature and tire pressure shown for each tire set.

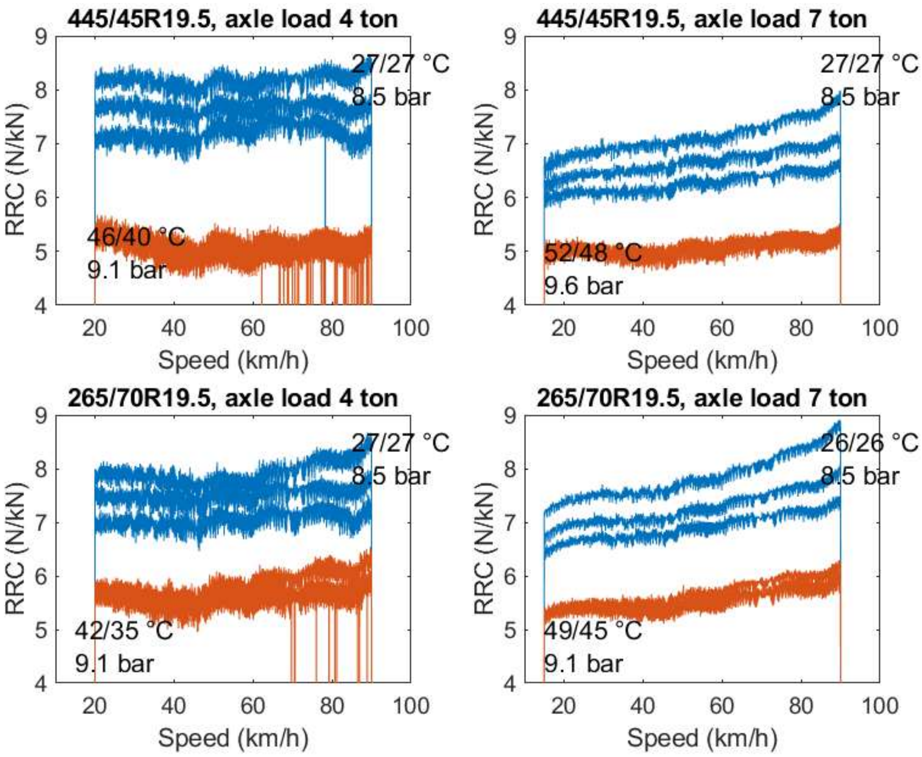

Figure 7. Rolling resistance coefficient of tires 445/45R19.5 and 265/70R19.5 as a function of speed for 4- and 7-tonnes axle load. Measurement with cold tires (blue curves) and with warm tires (red curves). Initial and final temperature and tire pressure shown for each tire set.

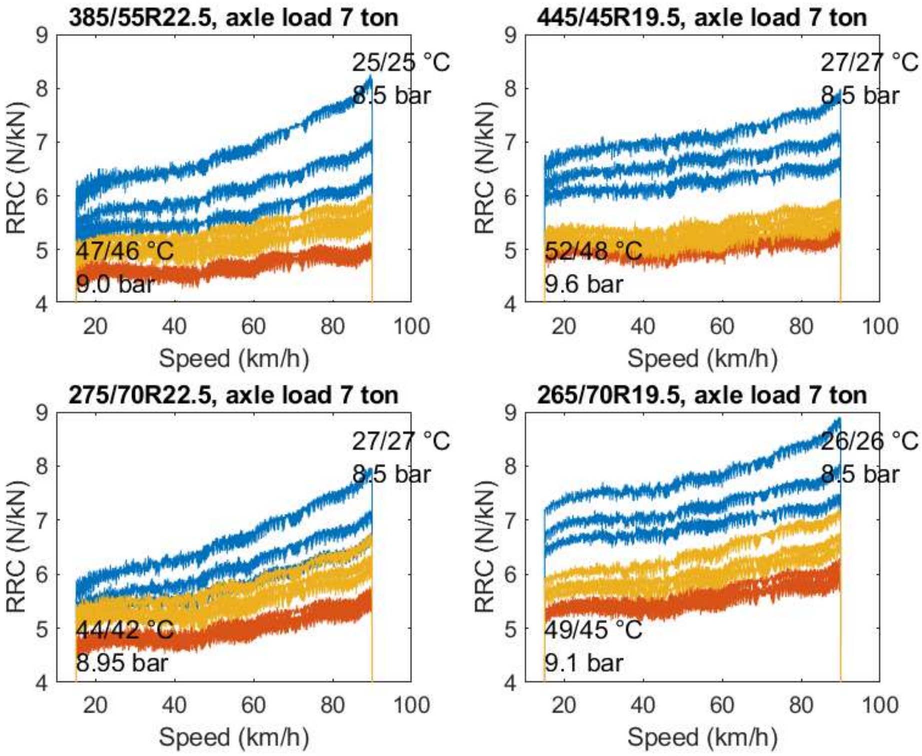

Figure 8. Rolling resistance coefficients of 385/55R22.5, 275/70R22.5, 445/45R19.5 and 265/70R19.5 tires as a function of speed and 7-tonnes axle load with cold tires (blue curves) starting with 8.5 bar tire pressure, continuing with warm tires (red curves), and with tire pressure decreased 2 bar from the pressure value after the warm measurement (yellow curves).

Representative rolling resistance coefficients for highway use are presented in Table 3. Values are average values for warm tire measurements within speed range of 70−90 km/h. Values are defined for axle load cases 4 tonnes with the reference pressure (8.5 bar set for cold tires), 7 tonnes with reference pressure, and 7 tonnes with reference pressure decreased with 2 bar.

Table 3. Average rolling resistance coefficients for highway speeds 70-90 km/h with warm tires.

Tire setup	RRC (N/kN) Load 4 tonne	RRC (N/kN) Load 7 tonne	RRC (N/kN) Load 7 tonne Pressure –2bar
385/55R22.5 Single	5.0	4.7	5.3
275/70R22.5 Dual	4.9	5.1	5.7
445/45R19.5 Single	5.0	5.0	5.3
265/70R19.5 Dual	5.6	5.3	6.1

5. Conclusions

Driving resistance values describing the rolling resistance force and the aerodynamic resistance force for a truck and full trailer combinations with two different bulk bodies, a tipper and cassette body, a swap body carrier with three swap bodies, and a timber body were measured. Rolling resistance values for different trailer tires were measured on a chassis dynamometer. Together these measurements give reference data for driving resistances presenting values for typical Finnish heavy vehicles. These values can be used for example as input values for simulation models, when analysing vehicle performance and energy consumption.

For coast-down measurements, to define the total driving resistance force of different vehicle combinations, vehicles were taken from their normal operation directly to the testing field. Before the actual testing, the tire pressures were checked to be in normal range, and each vehicle was warmed up to stabilize temperature dependent losses of tires and driveline. Due to the short testing period more detailed inspections, for example measurement of axle misalignments, could not be performed.

Coast-down measurements were performed under slightly varying weather and wind conditions. The effect of arbitrary wind was decreased using multiple test runs and opposite driving directions. The effect of air flow was also considered during the data post-processing, but due to the non-linearity and complex nature of side wind effects, it cannot be fully compensated from the results.

Driving resistance values defined from coast-down measurements present the total resistance force acting on the vehicle including rolling resistance, aerodynamic resistance and driveline resistances. Measurement of the driveline resistance would have required either extra sensors to the driveline, or an extra measurement on the chassis dynamometer, which was not possible during the measurement campaign. In this case the driveline resistances of comparable vehicles were used to estimate the resistance forces for rolling resistance and aerodynamic resistance without driveline losses.

Tire measurements on the chassis dynamometer were made with unworn and new tires designed for free rolling. Each set presents a typical tire setup used in trailer axles. Results give the rolling resistance coefficient as a function of driving speed. With an axle load of 7 tonnes, which can be thought to present an average axle load, rolling resistance on highway driving speeds is lower for single tires compared to dual tires, and is lower for tires with the rim size of 22.5” compared to the rim size of 19.5”. The decrease of tire pressure from the starting value around 9 bar to around 7 bar increased the rolling resistance coefficient on average by 11 %.

The effect of different trailer tire setups and corresponding rolling resistances on the road loads of a heavy vehicle combination are shown in Table 4. Road loads are defined for a vehicle combination of 76 tonne gross vehicle weight with 34 tonnes truck and 42 tonnes trailer. For the truck, a constant rolling resistance coefficient of 5.5 kN/N is assumed. For the trailer, rolling resistance coefficients for different tire setups with axle load of 7 tonnes shown in Table 3 are used. These values are extracted as an average in the speed range of 70−90 km/h representing highway driving. The aerodynamic resistance has C_DA coefficient of 9 m^2, air density of 1.25 kg/m^3, and driving speed of 70 km/h representing average speed of highway driving. The results show the road load power and the relative change of it compared to the tire setup of 385/55R22.5 Single, which gives the lowest road load power demand, and it is taken as the reference value. The road load calculation includes the share of rolling resistance force and aerodynamic force and therefore the relative change is comparable to the vehicle energy consumption, when concentrating only on the driving without auxiliary consumptions. Based on the measured tire rolling resistances and the assumptions made, the effect of trailer tire setups on the vehicle energy consumption is up to +4 %. With the decreased tire pressure, the change of the road load power is in a range of +4 % to +10 %.

Table 4. Road load force and power estimation with different trailer tire setups for a truck (34 tonne) and full trailer (42 tonne) combination with aerodynamic resistance C_DA of 9 m^2 and driving speed of 70 km/h.

Tire setup	Aero-dynamic resistance (N)	Truck rolling resistance (N)	Trailer rolling resistance (N)	Road load power (kW)	Change (%)
Tire pressure around 9 bar (the reference tire pressure 8.5 bar set for cold tires)					
385/55R22.5 Single	2127	1834	1936	135	Reference
275/70R22.5 Dual	2127	1834	2101	139	3 %
445/45R19.5 Single	2127	1834	2060	138	2 %
265/70R19.5 Dual	2127	1834	2184	141	4 %
Tire pressure around 7 bar (decreased by 2 bar)					
385/55R22.5 Single	2127	1834	2184	119	4 %
275/70R22.5 Dual	2127	1834	2349	123	7 %
445/45R19.5 Single	2127	1834	2184	119	4 %
265/70R19.5 Dual	2127	1834	2513	126	10 %

Tire measurement results also emphasize the effect of tire temperature on their rolling resistance. Figure 9 presents an example of rolling resistance coefficient development during the warm-up phase. Temperature at the beginning of the warm-up phase was 28 °C and at the end around 45 °C, and it takes around 45−60 min to reach the stabilized temperature. At the same time the rolling resistance coefficient decreased on average 25 %. For the typical driving situation, interesting information is the tire temperature and at the same time the rolling resistance of the tire, which depends for example on the axle load, ambient temperature, and driving conditions.

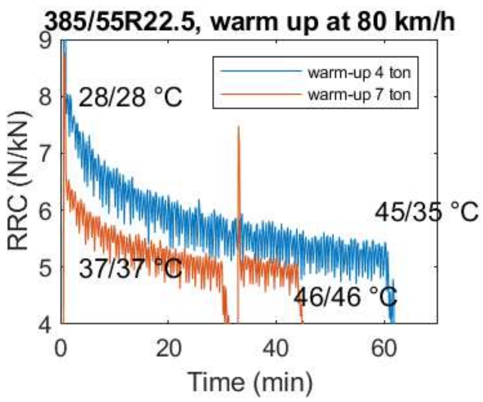

Figure 9. Tire rolling resistance as a function of time with constant speed of 80 km/h.

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