COMPARISON OF ROLLING AND AIR-DRAG RESISTANCE FOR LONGER AND SHORTER TRACTOR-TRAILER COMBINATIONS

				
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Abstract

This report addresses the magnitude of rolling and air-resistance for longer and shorter tractor-trailer combinations. The short combination is a tractor with a semitrailer (16.5 m) and the long is a tractor with two semitrailers and a dolly (32 m). The measurements were made on two different test tracks with two different vehicle combinations using two methods. The first method is the "constant speeds" and the second is the "coast down" method. The results from the two tests coincide to a large extent. It is observed that the rolling resistance becomes dominant over air resistance for the longer combinations at 80 km/h. Another conclusion is that at lower speeds (40-60 km/h) the rolling resistance becomes dominant even for short combinations.

Keywords: High Capacity Transport, Sweden, DUO-trailer, A-double, Air-drag, Rolling Resistance, Fuel consumption

1. Introduction

Over the last decade trials with High Capacity Transport (HCT) combinations have been carried out in Sweden. The driving force for these trials has been the reduction of CO_2 emissions, increased utilization of the infrastructure as well as transport efficiency. The maximum gross combination weight (GCW) was 60 tonnes and the maximum length was 25.25 meters in Sweden when the HCT project started in 2007. When one or both of these metrics are exceeded, we define it as an HCT transport. The trials have been carried out on special permissions from the Swedish Road Authorities. We have tested gross combination weights up to 90 tonnes and the overall combination length up to 32 m. The first HCT combination in Sweden was the (One More Pile –"En Trave Till") ETT-combination, the test started in January 2009, results were presented at the HVTT14 conference. DUO-trailer (tractor-semitrailer-dolly-semitrailer) tests started in February 2012, the gross combination weight (GCW) in use has varied between 40 and 80 ton. The average GCW turned out to be 60 tonnes with a standard deviation of 10 tonnes. The combination has 11 axels. The unladen weight is 30 tonnes and the average load is 30 tonnes. The regulation allows lifting of axles, gives possibilities for better traction, handling, and maneuverability for various load cases, road conditions, and topography. Moreover, it can give reduced tire wear and lower fuel consumption. Results were presented at HVTT15. The DUO-trailer test between Gothenburg and Malmo, a 280 km long motorway route along the E6. This section was chosen since motorways are designed to carry heavy traffic at high speed with the lowest possible number of accidents. The vehicle combinations are tested with permissions authorized by the Swedish Transport Agency (TSV 2018-5025 & TSV 2019-868). This allows combinations up to 33.5-meter length, 80 tonnes gross combination weight running at 80 km/h.

Air resistance depends on temperature, humidity, wind, and other factors. Rolling resistance depends on the type of tire, tire pressure, tread depth, road type, curvature, cross fall, and other factors. The two varied factors are number of axels and length of vehicle combination. Additional factors that influence the air and rolling resistance are not varied and the test shall be seen as a naturalistic study.

The simple rolling resistance model is not regarded as satisfactory. It assumes that the rolling resistance (F_{roll}) is only dependent on the actual weight (mg) and the rolling resistance coefficient (C_{rr}).

The present study focuses on rolling and air-drag resistance.

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2. Objectives

The study has been carried out to differentiate between the magnitude of air and rolling resistance, respectively.

This study is designed to find possible shortcomings and propose changes to the rolling resistance model.

By knowing the relative impact of air and rolling resistance, optimized complete transport solutions are possible.

3. Hypotheses

A. Due to the number of axles, energy dissipated by rolling resistance is greater than air-drag at normal driving conditions for longer combinations, opposed to shorter combinations
B. Rolling resistance increases faster than air-drag when the length and number of axles of the combination increases.
C. Lifting axels will have a greater impact on fuel consumption for longer combinations, with more axels, than for shorter combinations
D. The simple rolling resistance model is not adequate to explain the variation in rolling resistance
E. The rolling resistance coefficient is load dependent
F. The air resistance is independent of lifting of axels

4. Theory

The fuel consumption, on a flat surface and at a constant speed, depends on four constituents; Heat losses, internal mechanical resistance in the driveline, Air-drag and Rolling Resistance (including hubs). Heat losses from combustion are the greatest and internal mechanical losses are the smallest among the four. The situation for an electric vehicle has not been analyzed. However, this is not the aim of this study.
Air-drag and Rolling Resistance are comparable in size. A schematic power loss at 80 km/h on a flat road is shown in Figure 1.

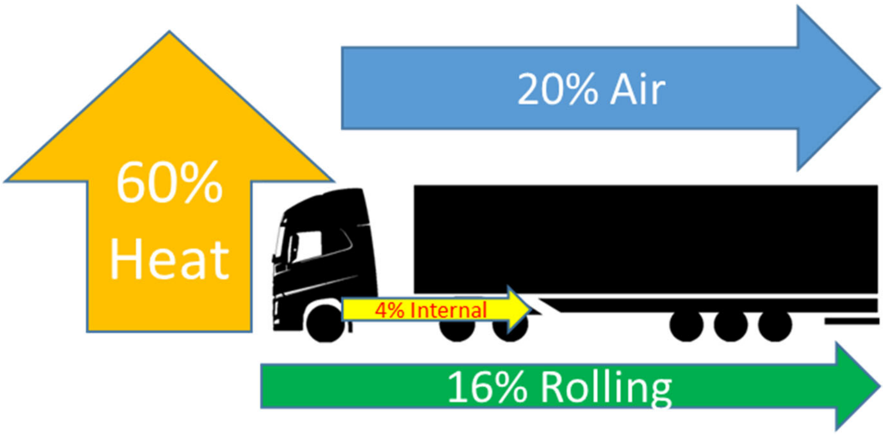

Figure 1 Schematic power use at 80 km/h on flat road

Our hypothesis is that the Rolling Resistance is increasing faster than the Air-drag for longer combinations compared to shorter combinations. The relative power use is shown in Figure 2.

Figure 2 Relative power use between Air drag and Rolling Resistance for single and duo trailer combinations at 80 km/h

The comparison between single and double semitrailer combinations is based on Air Drag Simulations in Helena Martini´s Thesis [1] and a simple rolling resistance model Equation 1. The rolling resistance coefficient is set to C_{rr}=0.005. The gross combination weight is *m* and *g* is the gravity on earth g=9.81 m/s^2.

$$F_{roll} = mgC_{rr} \qquad \textit{Equation 1}$$

However, this simple rolling resistance model does not account for the impact of lifted axles. Earlier findings [2] have shown that the rolling resistance is dependent on the number of axles that the load is distributed over. It is expected that the fuel consumption decreases substantially (~10%) when lifting five of the eleven axels on a duo-trailer, see Figure 3.

Figure 3 Duo-trailer with five lifted axels

Air resistance is often expressed according to Equation 2. "*A*" is the cross section of the vehicle, *ρ* is the air density, C_d is the drag coefficient and "*v*" is the vehicle speed.

$$F_{drag} = A\rho C_d \frac{v^2}{2} \qquad \textit{Equation 2}$$

The change in stored energy is zero at constant speed on a flat surface. Equation 3 describes the general situation.

$$\frac{dE}{dt} = v(F_{drive} - F_{drag} - F_{roll}) \qquad \textit{Equation 3}$$

Where F_{drive} is the driving force.

The driving force, Equation 4, can be measured using a specially designed wheel mounted on the driven axle.

$$F_{drive} = F_{drag} + F_{roll} \qquad \textit{Equation 4}$$

To reveal the separate impact of F_{drag} and F_{roll} various techniques are used. The total resistance was measured at various speeds as illustrated in Figure 4.

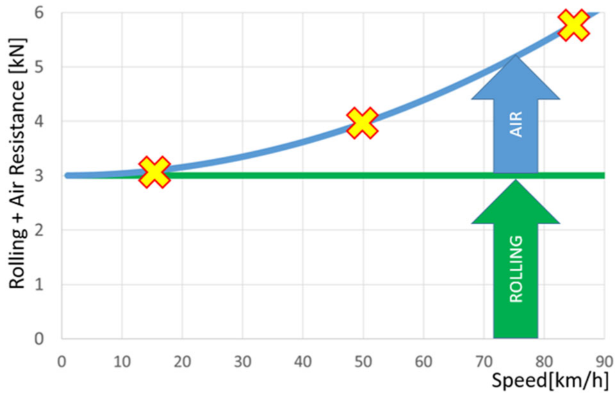

Figure 4 Schematic diagram of measured total resistance (rolling + air). Yellow and red cross (X) are examples of measurements at various speeds (15, 50 and 85 km/h).

The parameters C_d and C_{rr} are numerically fitted according to the least square method.
A supplementary method was used at a second test. This method is often described as coast down. The vehicle combination was accelerated to a predefined speed and the engine was disengaged by placing the gear into a neutral position. The speed of the vehicle combination is decreasing. The curvature of this deceleration is a function of the combined air and rolling resistance. Equation 5 shows the relationship. The parameters C_d and C_{rr} in the differential equation were numerically fitted using an iterative method. The start values for this iteration were the values from the constant speed method.

$$\frac{dE}{dt} = \frac{d}{dt}\left(\frac{mv^2}{2}\right) = -v(A\rho C_d \frac{v^2}{2} + mgC_{rr}) \qquad \textit{Equation 5}$$

The length of the straight and flat sections of the test area was not long enough for slowing down from 80 km/h all the way to 0 km/h. The test was modified to also start from lower speeds in order to overcome this problem.

5. Method

Four tests, as seen in Figure 5, were performed to reveal the relative impact of air-drag and rolling resistance. The first two units, tractor and semitrailer 1 are the same for all of the tests. The tractor and loaded first semitrailer weigh 24 tonnes and the dolly and second semitrailer weigh 22 tonnes. The combination with two semitrailers weights 46 tonnes.
The loads were placed so that the axle loads for the combinations were similar.

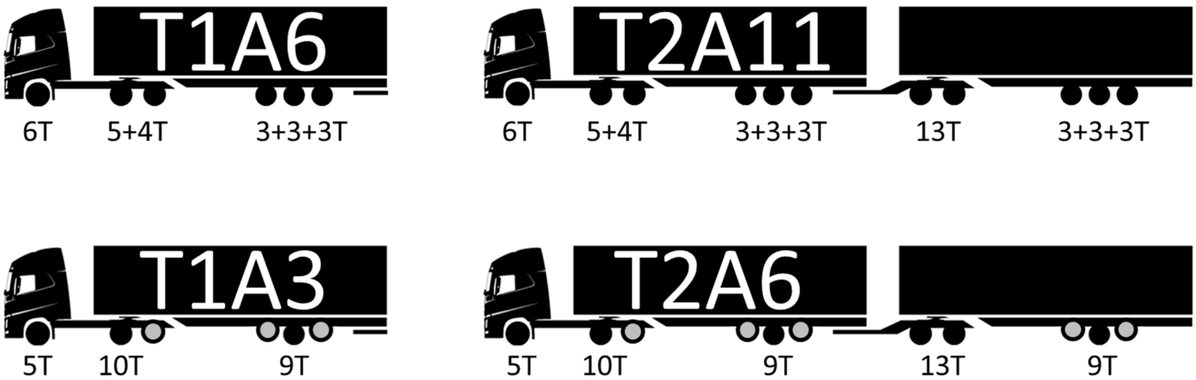

Figure 5 The four vehicle combinations in the tests. The letter T stands for trailers and A for axles. T1A3 indicates three axels used on the combination with one semitrailer.

The vehicle combinations were loaded so the maximum axle load was not exceeded when lifting the axles. The maximum axle loads in Sweden are 10 tonnes on a single axel (11,5 tonnes if driven), 18 tonnes on a boogie (19 driven road friendly) and 24 tonnes on a tridem.

6. Vehicle Combinations

Two different sets of vehicle combinations were used in this study. This was not by choice; it was due to availability. The first test period "Constant Speed" with a duo trailer from the HCT field test with Schenker in Sweden. After the tests the vehicle combination was put back in regular operation. This combination is shown in Figure 6. The Tractor is an FH16 with a 750 hp engine. The second driven axel is mechanically disengaged to allow the force measurement with the Kistler wheel on the first driven axel. The test was performed at Björkvik, a former Air Field near, Nyköping in Sweden.

*Figure 6 **Top and Bottom** the schematic combination with lifted and non-lifted axels. **Middle** the vehicle combination used in the Constant Speed test. Note that the axels are not lifted on the photo in the middle. The vehicle was used for measurements with all axles down as well as with five lifted axles.*

The combination used in the second test (Coast Down) measurements is a pick-and-mix combination from various advanced development projects. The reason for using this combination was an opening in time for verification of results from the Constant Speed test. The combination had been used for other types of measurements at the Volvo Proving Ground. The Tractor is an FH16 with a tandem axle lift. The first semitrailer had only a 20' container for weight balancing. The dolly has steering capabilities and a somewhat longer wheelbase. In these tests, this function was locked. The second semitrailer was the Volvo VEV semitrailer. The Coast Down combination is seen in Figure 7.

*Figure 7 **Top and Bottom** the schematic combination with lifted and non-lifted axels. **Middle** the vehicle combination used in the Coast Down test. Note that five axels are lifted on the photo in the middle; one on the tractor, two on the first semitrailer and two on the second semitrailer (not seen on the second semitrailer due to side covers). The vehicle was used for measurements with all axles down as well as with lifted axles.*

7. Results

7.1 Constant Speed test

The Constant Speed tests were executed over two consecutive days on a flat airstrip. The weather conditions were the same on both days; no wind, cloudy, high humidity, and around 8°C. The measured resistance is the sum of air and rolling resistance. The measurements are shown in Table 1 and Table 2.

Table 1 Measurements day 1. Total resistance for the test combinations.

Speed km/h	Force N			
	T1A6	*T1A3*	*T2A11*	*T2A6*
13	2462	2048	4041	3743
55	3569	3220	5702	5284
77	4592	4269	7002	6337
88	5409			

Table 2 Measurements day 2. Total resistance for the test combinations.

Speed km/h	Force N			
	T1A6	*T1A3*	*T2A11*	*T2A6*
10	2528			
22	2631	2275	4813	4037
33	2864	2517	4813	4233
44	3238	2848	5493	4575
55	3598	3192	5745	5074
66	4219	3732	6463	5805
77	4763	4107	6893	6027
88	5326	4893		

The data from the Constant Speed test were fitted to Equation 1, 2, 3, and 4 using least square multiple regression analysis. The air resistance, C_d, is the same for the single trailer combinations independent of the number of axles lifted. This is a boundary condition in the regression analysis. The same applies to the C_d for the duo trailer combinations. The C_{rr} values are estimated separately but turned out to be 0.01 for the two combinations with all axels down and 0.0085 for the two combinations with lifted axles. The results from the regression are found in Table 3.

Table 3 Multiple regression of data day 1&2. Co-estimation of C_d and C_{rr}.

	T1A6	*T1A3*	*T2A11*	*T2A6*
C_d	0,72	0,72	0,8	0,8
C_{rr}	0,01	0,0085	0,01	0,0085

The R^2 for this multiple regression is 98.7 % which is a good fit.

7.2 Coast Down

The Coast Down test used retardation as the measuring principle. Each set started at 80 km/h (22.2 m/s) and the time for reaching the lower speeds is shown in Table 4. This test was also performed over two days with very similar conditions; no wind, clear blue skies, and the temperature was around 0°C.

Table 4 Coast down. Time in seconds when the speed is reached for the four different combinations. Each test started at 80 km/h.

Speed (km/h)	Time (s)			
	T1A6	***T1A3***	***T2A11***	***T2A6***
80	0	0	0	0
70	16	18	20	26
60	35	38	47	57
50	60	66	74	86
40	86	100	105	123
30	115	131	138	162
20	147	168	176	205
10	187	214	218	255
0	230	264	260	310

The data from the Coast Down test were fitted to Equation 5. The values C_d and C_{rr} were used as initial values for the iterations in solving the differential equation. The same boundary condition for C_d was used in these calculations. The air resistance, C_d, is the same for the single trailer independent of the number of axles. The same applies to the C_d for the duo trailer. The C_{rr} values turned out to be 0.007 for the two combinations with all axels down. The C_{rr} values for the vehicles with lifted axles differed somewhat; 0.006 for the single trailer with lifted axles and 0.0055 for the duo trailer with lifted axles. The results from the regression are found in Table 5.

Table 5 – Multiple regression of data from the Coast Down measurements. Co-estimation of C_d and C_{rr}.

	T1A6	***T1A3***	***T2A11***	***T2A6***
C_d	0,74	0,74	0,85	0,85
C_{rr}	0,007	0,006	0,007	0,0055

The R^2 for this multiple regression is 99.8 % which is an extremely good fit. The residual sum of squares is 648 compared to 277 109 which is the total sum.

7.3 Comparison of the numeric solutions from the Constant Speed & Coast Down Tests

The absolute values differ somewhat for the Air drag, which is expected. But they show an extremely good correlation which is shown in Figure 8. The Air drag coefficient is not any detectable level influenced by lifting axles.

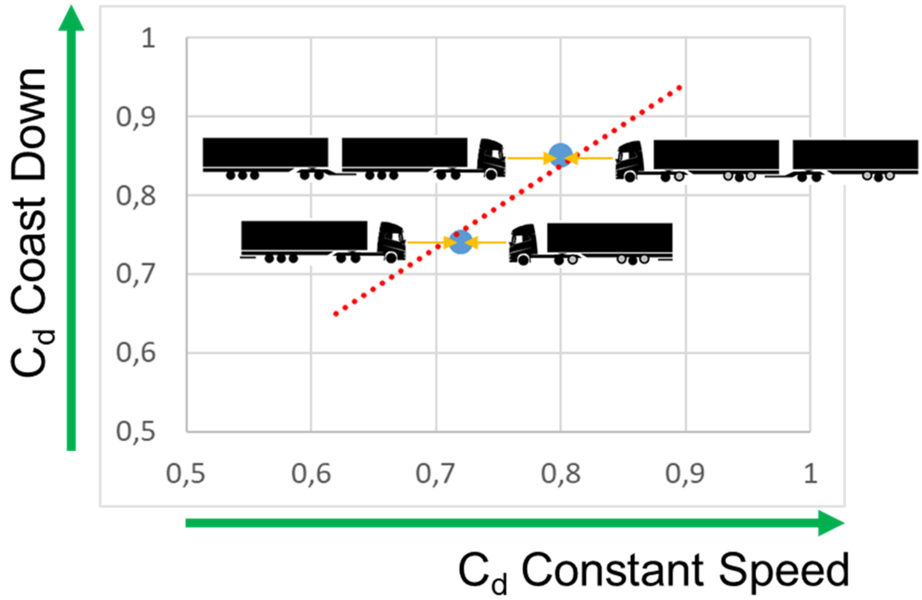

Figure 8 Correlation between Air drag coefficient (Cd) estimations from the Constant Speed and Coast Down Tests. Blue circle estimations of Cd using the two methods. Red line shows correlation between the Cd estimations for the single and duo trailers.

The absolute values differ for the Rolling Resistance Coefficient (C_{rr}) also. But they show a good correlation which is shown in Figure 9. It is observed that the Rolling Resistance Coefficient is dependent on lifting axels.

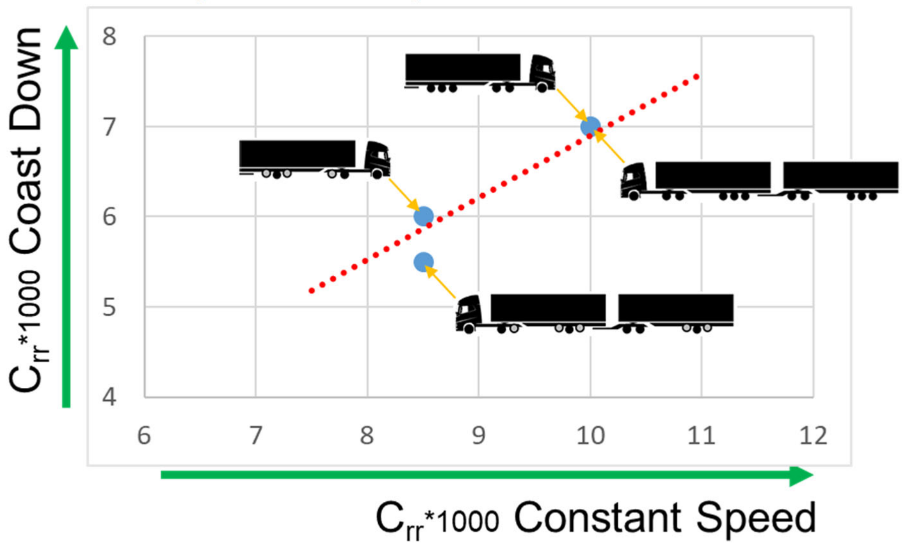

*Figure 9 Correlation between Rolling Resistance coefficient (Crr*1000) estimations from the Constant Speed and Coast Down Tests. Blue circle estimations of Crr using the two methods. Red line shows correlation between the Crr estimations for the single and duo trailers.*

7.4 Graphic representation of measurements and numeric solutions

The constant speeds measurements and numeric solutions are shown in Figure 10. The air and rolling resistance models gives a very good fit of the observed variation. The force is the sum of air and roll resistance at each speed.

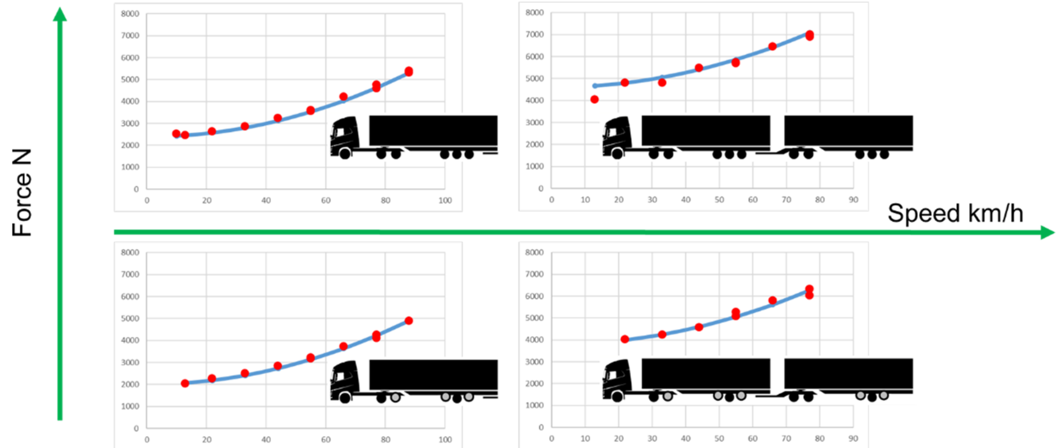

Figure 10 Comparison of measurements (red) and the numeric solution (blue) Constant Speed tests

The coast down measurement and numeric solutions are shown in Figure 11. The air and rolling resistance models gives an extremely good fit of the observed variation. The speed is decreasing from 80 km/h (22.2 m/s) down to 0.

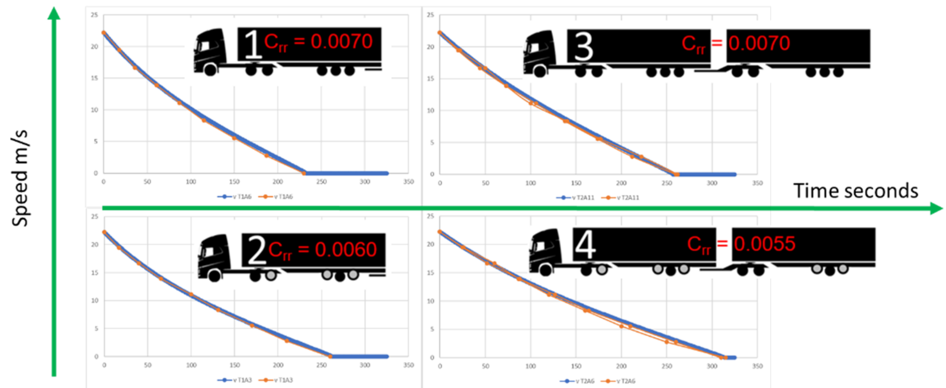

Figure 11 Comparison of measurements (red) and the numeric solution (blue) for Coast Down test

7.5 Rolling Resistance coefficient is load dependent

This section elaborates in depth on the hypothesis D and E and Equation 1.

D. The simple rolling resistance model is not adequate to explain the variation in rolling resistance
E. The rolling resistance coefficient is load dependent

$$F_{roll} = mgC_{rr} \qquad \textit{Equation 1}$$

The null hypothesis H_0 is that the rolling resistance is independent if axels are lifted or not.

The gross combination weight for Constant Speed and Coast Down tests has been the same. The single trailer has had a GCW of 24 tonnes and the duo trailer has had a GCW of 46 tonnes. The only difference is the number of axels lifted. If Equation 1 is valid, or good enough, there would not be any statistical significance in the apparent measured difference.

The data from the Constant Speed test are used for calculating the difference in force. A paired t-test is made between lifted and not lifted axel on each combination. The t-value for the single trailer is 13,5 which shows that the null hypothesis can be rejected. The t-value for the duo trailer is 9,8 which also shows that the null hypothesis can be rejected. A t-value of 2 is often used to reject the null hypothesis. The higher the t-value the better.

The same t-test can be done for the Coast Down measurements. But here it can be shown what happens if the C_{rr} is forced to the same value instead of allowing each of estimating a separate value for each of the coast down tests. The C_{rr} and residual sum of squares, for each setup, are shown in Table 5. The best fit for a common C_{rr} (0,0064) is SS_{res} = 4863 which is more than 7 times higher than SS_{res} = 648 for the separate C_{rr} for each combination. The obvious deduction is that the rolling resistance is dependent on the number of axles. The simple rolling resistance model is not applicable.

Table 5 Residual sum of squares (SS_{res}) for each set of rolling resistance coefficient (C_{rr}). The C_d is 0,74 always for the single trailer and 0,85 for the duo trailer in numerical solutions for equation 5.

	T1A6	T1A3	T2A11	T2A6	SS_{res}
C_d	*0,74*	*0,74*	*0,85*	*0,85*	
C_{rr}	0,007	0,006	0,007	0,0055	**648**
C_{rr}	0,007	0,007	0,007	0,007	**7681**
C_{rr}	0,0065	0,0065	0,0065	0,0065	**4903**
C_{rr}	0,0064	0,0064	0,0064	0,0064	**4863**
C_{rr}	0,0063	0,0063	0,0063	0,0063	**5089**
C_{rr}	0,006	0,006	0,006	0,006	**6779**
C_{rr}	0,0055	0,0055	0,0055	0,0055	**16 607**
C_d	*0,74*	*0,74*	*0,85*	*0,85*	

7.6 The air resistance is independent on lifting of axels

This section shows one example of how air resistance is derived. The example is from a Constant Speed test with a single trailer with lifted and without lifted axels. According to Equation 2 the air drag force is proportional to the square of the speed. The intercept on the Y-axis is the rolling resistance. The slope of the line in Figure 12 is thus proportional to the C_d value for the specific combination. The two lines parallel and separated only by the difference in rolling resistance. The estimated C_d value can differ slightly, but the Hypothesis F cannot be rejected. Hence, the air resistance is regarded as independent on axels on road.

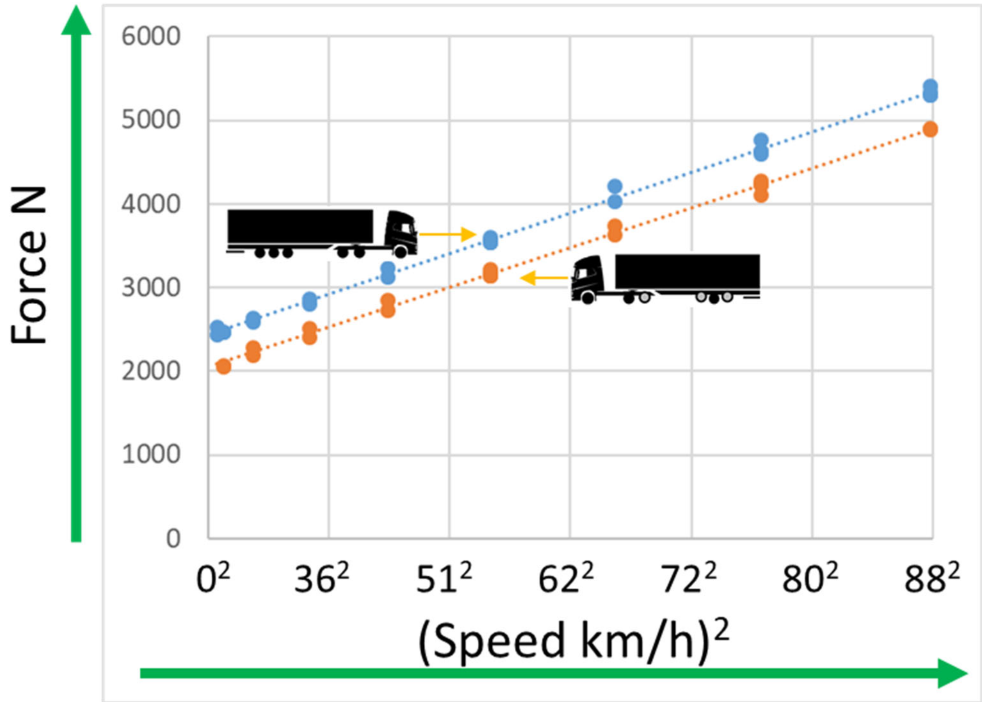

Figure 12 *X-axis: Speed to the power of two. Y-axis: is the combined air and roll resistance. Force measured during Constant Speed test. Blue, all axels down, and Red 3 of 6 axels lifted. Dotted lines are linear fit in accordance with European test method[4] for air resitance. The two lines are parallel which means that the air resistance is the same for both cases.*

8. Discussion

In this work, the length and number of axels are coupled. The number of axels in a combination is depending on goods density, load fill rate and load position. This means that most combinations in practice need more axels than theoretically needed.

The Duo-trailer combination used in this work is designed to handle goods with large variation in density.

For combinations that transport goods with similar density, axle management is important if empty return or pickup distances are involved.

However, with a vehicle combination that always has the same density goods and volume this need not be the case.

9. Conclusions

- Rolling resistance become larger than air resistance for longer and heavier vehicle combinations at 80 km/h
  → *Hypotheses A and B cannot be rejected*
- The simple rolling resistance model is not sufficient to predict decreased rolling resistance when lifting axels. The rolling resistance coefficient is load dependent.
  → *Hypothesis D cannot be rejected*
- The more axles in a combination the more important is the tyre performance
  → *Derived from not rejecting Hypothesis E*
- Longer combinations have an inherent lower relative air resistance than shorter combinations → *Derived from not rejecting Hypotheses A, B & E*
- The fuel measurements, when lifting axles for single and double trailers, should be tested → *Hypothesis C could not be disputed due to lack of measurements*
- The air resistance is independent on lifting of axels
  → *Hypothesis E cannot be rejected*
- Multiple constant speeds in the air and roll resistance estimation[4] should give better predictions of C_d and C_{rr}

10. Recommendations and further work

Hypothesis C could not be disputed since fuel measurements have not been made. Set up fuel measurement for the four combinations at 80 and 60 km/h. Preferably with the option to have both one and two driven axels on the tractor. Make an investigation of the actual speeds. Lower speeds than 80 km/h may result in that shorter combinations also have higher rolling resistance than air resistance.

11. References

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2. HVTT14 2016	CO-optimizing multi vehicle combinations, fuel consumption & traction in slippery condition	Larsson, Cider, Pettersson
3. HVTT15 2018	Duo Trailer an Innovative Transport Solution CO-optimizing multi vehicle combinations	Cider, Jarlsson, Larsson
4. Standard	Annex VIII of the EU regulation no. 2017/2400	

12. ABBREVIATIONS & NOMENCLATURE

A	Front cross section of the vehicle m^2
CO_2	Carbon Dioxide (global warming greenhouse gas)
C_d	Air Drag Resistance
C_{rr}	Rolling Resistance Coefficient
Dolly	 Trailer with only a fifth wheel
DUO-trailer	Tractor + Semi-trailer + Dolly + Semi-trailer
ETT	En Trave Till - One Pile More
F_{drag} , $F_{drive,}$, F_{roll}	Aerodynamic Resistance, Driving force, Rolling Resistance (N)
FFI	Strategic Vehicle Research and Innovation – (Swedish program)
g	Acceleration of gravity ~ 9,81 m/s^2
GCW	Gross Combination Weight
GTT	Group Truck Technology
GVW	Gross Vehicle Weight
HCT	High Capacity Transport
HVTT	Heavy Vehicle Transport Technology
kg	SI unit for mass = The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be 6.62607015×10^{-34} when expressed in the unit J·s, which is equal to $kg \cdot m^2 \cdot s^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.
litre	1/1000 m^3
m	Mass in kg
m	The meter is defined to be the distance light travels through a vacuum in exactly 1/299792458 seconds
M	Mass of goods transported {metric tonne=1000 kg}
N	The newton (symbol: N) is the SI unit of force. It is named after Sir Isaac Newton because of his work on classical mechanics. A newton is how much force is required to make a mass of one kilogram accelerate at a rate of one metre per second squared
R^2	Is the sum of the squares of residuals (deviations predicted from actual empirical values of data). It is a measure of the discrepancy between the data and an estimation model. A small R^2 indicates a tight fit of the model to the data. It is used as an optimality criterion in parameter selection and model selection. In general, total sum of squares = explained sum of squares + residual sum of squares.
s	Second (time) = the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9192631770 when expressed in the unit Hz, which is equal to s−1
Semi-trailer	 Trailer with kingpin and rear axels
tonne	1000 kg
t-test	statistical hypothesis test in which the test statistic follows a Student's t-distribution under the null hypothesis.
v	Speed m/s
ρ	Air density ~ 1,3 kg/m^3