# ANALYSIS OF AXLE CONFIGURATION, TIRE PRESSURE, AND TIRE TEMPERATURE ON FUEL CONSUMPTION OF HCT COMBINATIONS

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## Abstract

This paper will focus on the effect on fuel consumption of lifting of axles on vehicle combinations such as High-Capacity Transports.

There are several reasons why High-Capacity Transports (HCT) are commonly used to increase transport efficiency. This article answers the question why HCT combinations are more fuel-efficient than standard combinations by focusing on the impact of axles and tires. Aerodynamic measures are important, but rolling resistance is just as important. In many cases, rolling resistance influences fuel consumption more than aerodynamic resistance. Several experiments were performed at the high-speed track at Hällered, Sweden to analyse the impact on fuel consumption of the lifting of one or more axles in single-trailer and duo-trailer combinations, as well as in dry versus heavy rain conditions. When 5 of 11 axles in a duo-trailer combination are lifted, the fuel consumption decreases by 8 %. The corresponding figure for a single-trailer combination is a decrease of 3 % when 3 of 6 axles are lifted. The force on the dolly drawbar was also measured and was found to decrease by about 14 % when 2 axles on the second semitrailer were lifted. The tire pressure increases by about 1 bar when driving at a constant speed of 80 km/h and the tire temperature takes about 1 hour to reach a steady state. Both fuel consumption and rolling resistance decrease continuously during this time. However, our data show that the main reason for this reduction in rolling resistance is not the increase in tire pressure, but rather the increase in tire temperature.

**Keywords:**
High-capacity transport, HCT, axles lifting, tires, rolling resistance, energy usage, fuel consumption

## 1. Introduction & background

Why are HCT combinations more fuel-efficient than standard combinations? In a series of HVTT conferences, we have reported on the improved fuel efficiency of HCT combinations. At the HVTT17 conference we will delve deeper into our understanding of the impact of tires and axle management.

There are several reasons why HCT combinations are more fuel efficient. The first is that they can transport a greater load. The second is that the unladen weight of the combination increases less than the laden weight does. In other words, we are pulling more load per weight-unit of the truck combination. Third, the air drag of longer combinations is lower than the combined air drag of separate units carrying the same load. In this study, these advantages are taken for granted and our work will focus on the fuel-consumption factors of tires and how axle management can influence them. The HCT project has reached the conclusion that axle management is very important. The greatest advantage is when driving empty or with cargo that is below the combination's weight limit, for example low-density cargo.

The role tires play in real fuel efficiency is very important. It takes approximately one hour for a tire to reach a steady-state temperature when driving on a flat road at a constant speed. In that steady state, we can claim to have reached a constant rolling resistance coefficient. In all other cases, the rolling resistance is a function of not only the load but also of pressure, temperature, rain, air flow, road conditions, and several other aspects.

The objective of this work is to identify which axles can be lifted in vehicle combinations and to understand the factors that influence the rolling resistance of tires.

## 2. Method

This study is performed with a test combination with 5 liftable axles on test track. Two different combinations can be used by decoupling the last two units. The tests have been completed during stable weather conditions with no or very little wind. There was no rain except for one test were the impact of precipitation on fuel consumption was measured. The axle loads are chosen so all 5 liftable axles can be lifted within legal maximum weights. Fuel consumption is measured by means of the electronic control unit for the diesel engine.

The independent variables are number of axles lifted for the test combination. Dependent variables are tire temperature, and tire pressure, fuel consumption, and coupling force.

Each test was done in an A-B-A procedure. The first setting (A) was repeated after the intervention setting (B) in order to minimize the risk of confounding factors. Each setting was run between 6 and 10 laps in order to reach a steady state.

A test combination equipped with tire sensors was used at Volvo Hällered Proving Ground outside Borås in Sweden. The combination is shown in Figure 1.


**Figure 1 – A duo-trailer combination with eleven axles, of which five axles are liftable**

A tire sensor that measures the tire pressure and tire temperature was installed in each of the 24 tires of the combination. Figure 2 shows the location of the sensor in the front tire.

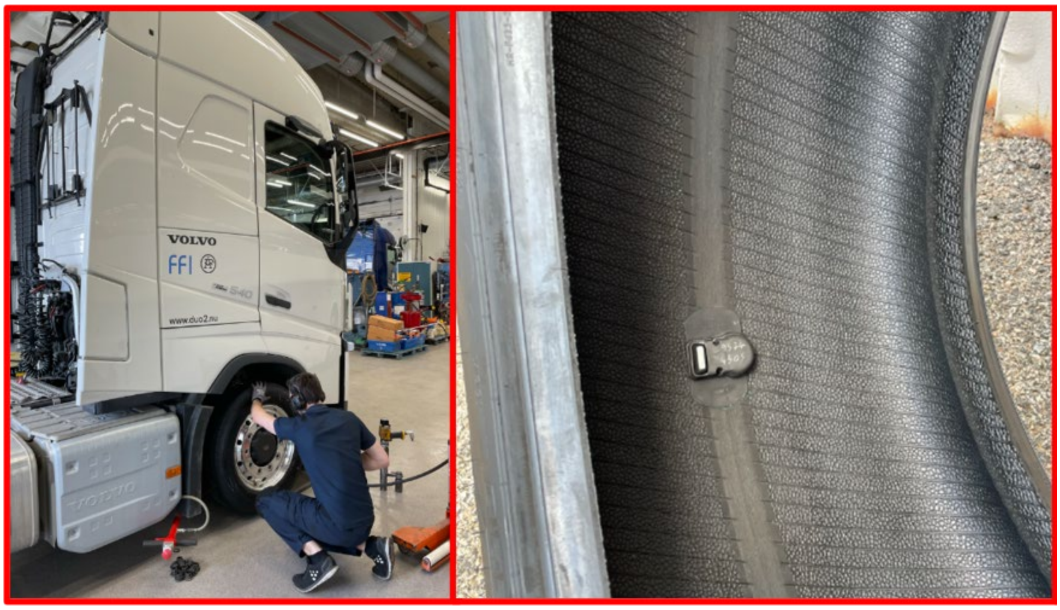



**Figure 2 – Placement of tire sensor in front tire**

A force sensor was installed on the drawbar of the dolly that connects the two semitrailers. The position of the sensor is shown in Figure 3.


**Figure 3 – Close-up of position of the force sensor on the dolly**

The test track used was the main high-speed track at Hällered, Sweden. The track has a length of 6.2 km and all tests were run driving clockwise at a constant speed of 80 km/h. Figure 4 shows the shape of the track. The two curves have a slope of 0.6 %; the first downwards, the second upwards. The two straight sections are horizontal. Each curve is 1900 m long and the straight parts are 1200 m long.

Method for evaluation of rolling resistance and air drag. Each setup was run at 80 km/h until a steady state was reached for fuel consumption estimation. A set of coast-down measurements were then performed by setting the gearbox in neutral and recording the speed reduction over time. Equation 1 was determined by fitting the speed reduction of the 4 various combinations using an iterative method.

$$\frac{d}{dt}\left(\frac{mv^2}{2}\right) = -v\left(A\rho C_d \frac{v^2}{2} + mgC_{rr}\right) \tag{1}$$

| | | | |
|---|---|---|---|
| m | Weight | v | Flow velocity |
| A | Reference area | ρ | Mass density |
| $C_d$ | Drag coefficient | g | Gravity constant |
| $C_{rr}$ | Rolling-resistance coefficient | | |

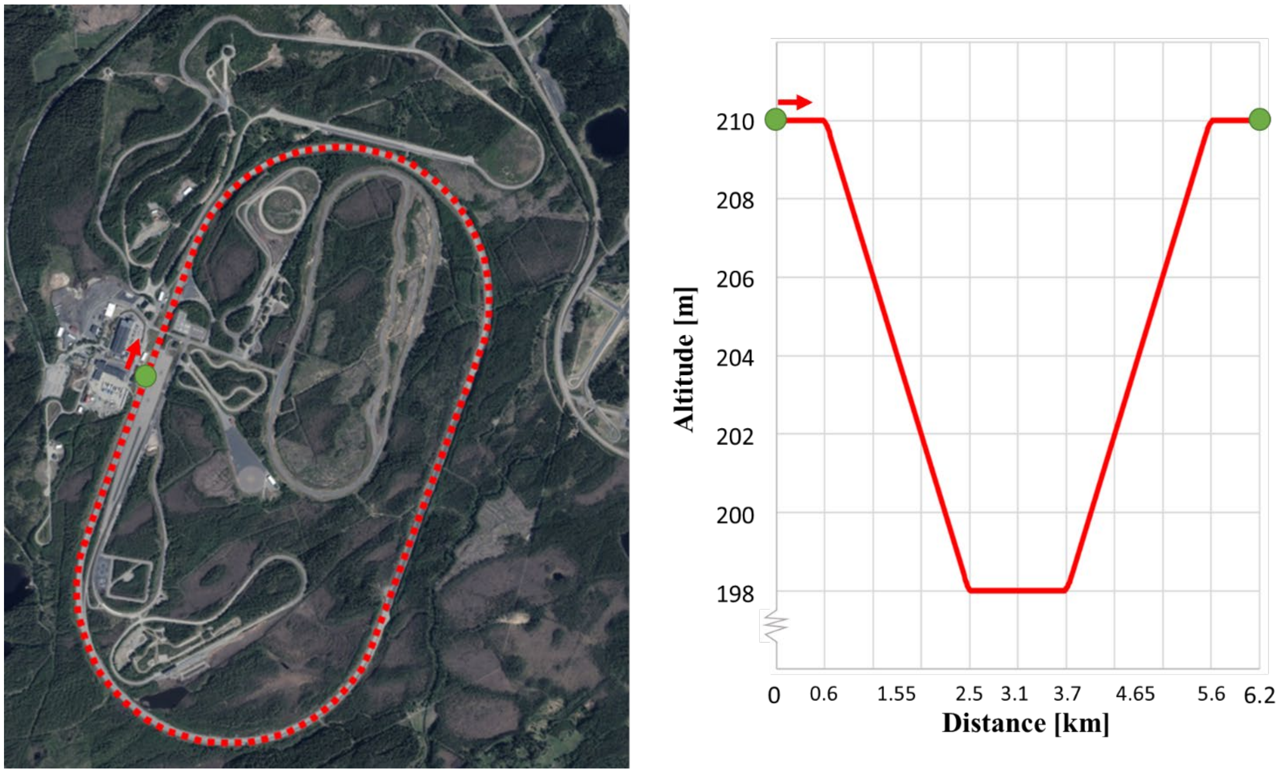



**Figure 4 – Main high-speed track at Hällered with a length of 6.2 km**

## 3. Results

Various analyses and results are presented in this chapter.

### 3.1. The tire sensors

The sensor-equipped Goodyear tires report data for our experiments at frequent intervals. Figure 5 shows the tire temperature and the tire pressure during an 8-hour test cycle, including breaks. The vehicle combination was allowed to cool down from hour 3.5 to hour 8 until it reached the initial pressure and temperature in the tires.

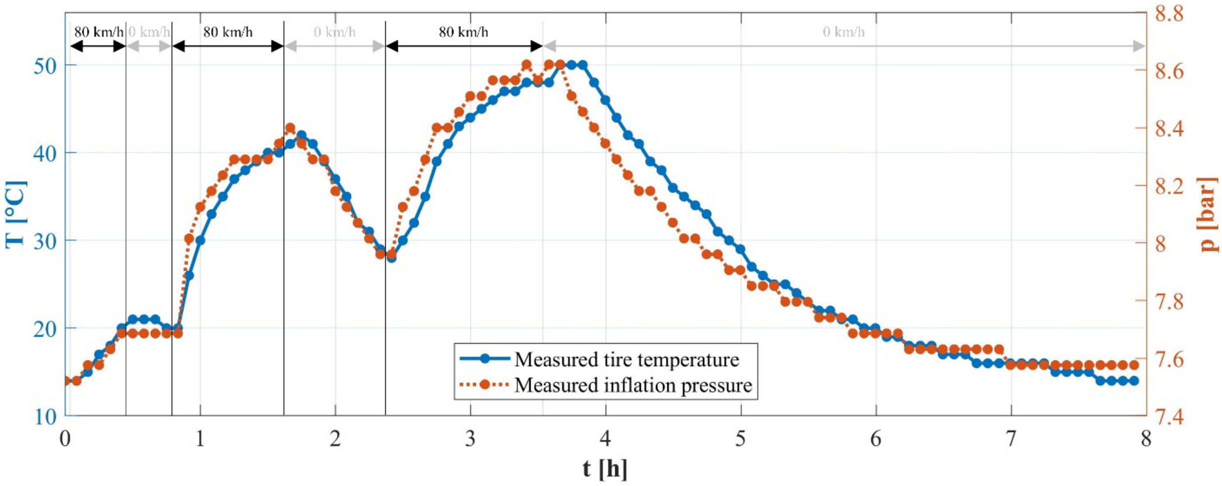



**Figure 5 – Distribution cycle of pressure and temperature for a tire on the driving axle during the day**

The correlation between pressure and temperature is extremely strong. The ambient temperature was 15 °C and the pressure at start was 7.5 bar. As we can see, the temperature lags slightly behind the pressure.

The ideal gas law in Equation 2 describes the covariation of pressure and temperature given that the volume is constant, and the number of gas molecules does not change.

$$pV = nRT \quad (2)$$

p Tire pressure
V Enclosed tire volume
n Number of gas molecules
R Ideal gas constant
T Tire temperature

While the tire's air volume may be marginally influenced by pressure, we assume it to be negligeable. The number of gas molecules enclosed in the tire is constant. If it isn't, the covariation of pressure and temperature is broken.

### 3.2. Empirical model for reaching the steady state

All time-dependent measurements of pressure and temperature follow the same pattern, which is described in Equation 3, while Figure 6 compares measured and predicted tire temperature.

$$T_{sim} = T_{ss} - (T_{ss} - T_{amb})e^{-\frac{t}{t_k}} \quad (3)$$

$T_{sim}(t)$ Temperature from simulation as a function of time
$T_{ss}$ Steady-state temperature under constant driving conditions
$T_{amb}$ Ambient temperature
t Time
$t_k$ Time constant for the specific driving condition

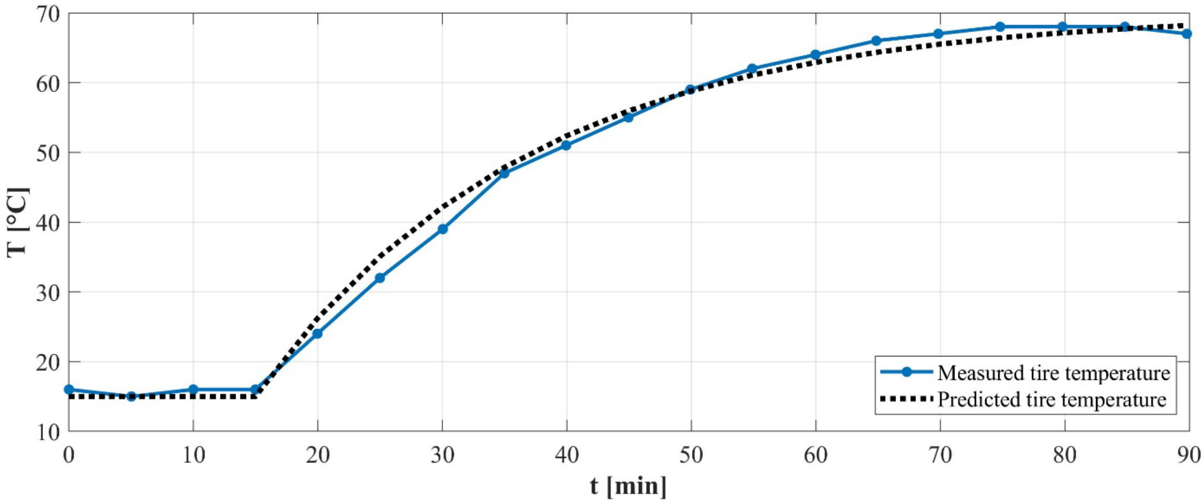



**Figure 6 – Measured and predicted tire temperature over time while driving at 80 km/h**

### 3.3. Force measurement

The force sensor (manufacturer: VBG Group Truck Equipment AB) registers loads in three dimensions. The sensor is attached to the drawbar eye of the dolly. In Figure 7, the data for the fuel consumption have been superimposed on the data for the longitudinal force in the drawbar to enable comparison and visualise the correlation. Combination A had two raised axles on the second semitrailer, while no axle was raised in combination B. Test conditions A and B were both evaluated over 10 laps on the high-speed track. The correlation between fuel consumption and longitudinal force is good in both tests. The change in track altitude influenced both measured values and even led to compressive longitudinal forces through pushing of the dolly and semitrailer 2. The fuel consumption and the longitudinal force decreased over time, which revealed the influence of rolling resistance as the vehicle was driven at a constant speed with constant air drag. The rolling resistance decreased over time as the tire temperature increased until it reached a stable state.

The force observed in correlation with fuel consumption was the force generated in the vehicle combination that is mainly caused by changes in the required engine torque. The force signal was low-pass filtered to determine the tracking and braking forces, in accordance with the conclusions reached by "Svensson, Nilsson and Fröjd (2016)". The 10 peaks at 250 s, 500 s, 750 s ... 2750 s are at the same location of each lap on the test track.

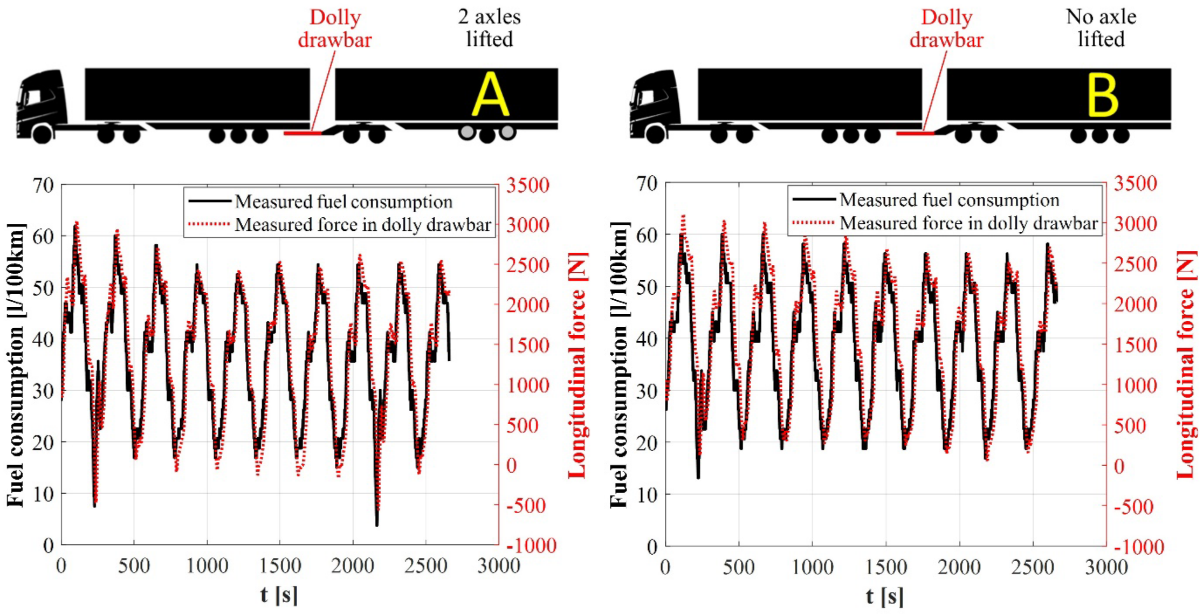



**Figure 7 - Correlation between measured fuel consumption and force in the drawbar eye; A) 2 axles of the second semitrailer lifted; B) No axles lifted**

The tests with the force sensor were divided into three versions (A1, A2 and B), as shown in Table 1. A1 and A2 are replications with two lifted axles on the second semitrailer and show little variation in the measured results. The last 3 laps of each test condition are considered to use only steady state data. Lifting 2 axles on the second semitrailer reduces the fuel consumption by 6.2 % and the force by 13.9 % compared to the reference test B where no axles have been lifted.

**Table 1 – Fuel consumption and force on the drawbar of the dolly**

| Version | Axles [#] | Fuel consumption [l/100 km] | Reduction in fuel consumption [%] | Force [N] | Reduction in force [%] |
|---|---|---|---|---|---|
| A1 | 9 | 34.9 | 5.9 | 1286 | 12.3 |
| B | 11 | 37.1 | - (reference) | 1467 | - (reference) |
| A2 | 9 | 34.7 | 6.5 | 1241 | 15.4 |

### 3.4. Impact of rain on tires and fuel consumption

The testing under consistent conditions was disturbed on one of the test days by heavy rain, which turned out to be a "lucky accident". On this day the weather changed from clear blue skies to heavy rain (>10 mm/h). With this quantity of rain, the road was constantly covered by up to 3 cm of water. The impact of this water on the tires is shown in Figure 8. During the first 30 minutes without rain, the tire pressure and temperature increased as usual. During the following 30 minutes of heavy rain, the pressure and temperature decreased.

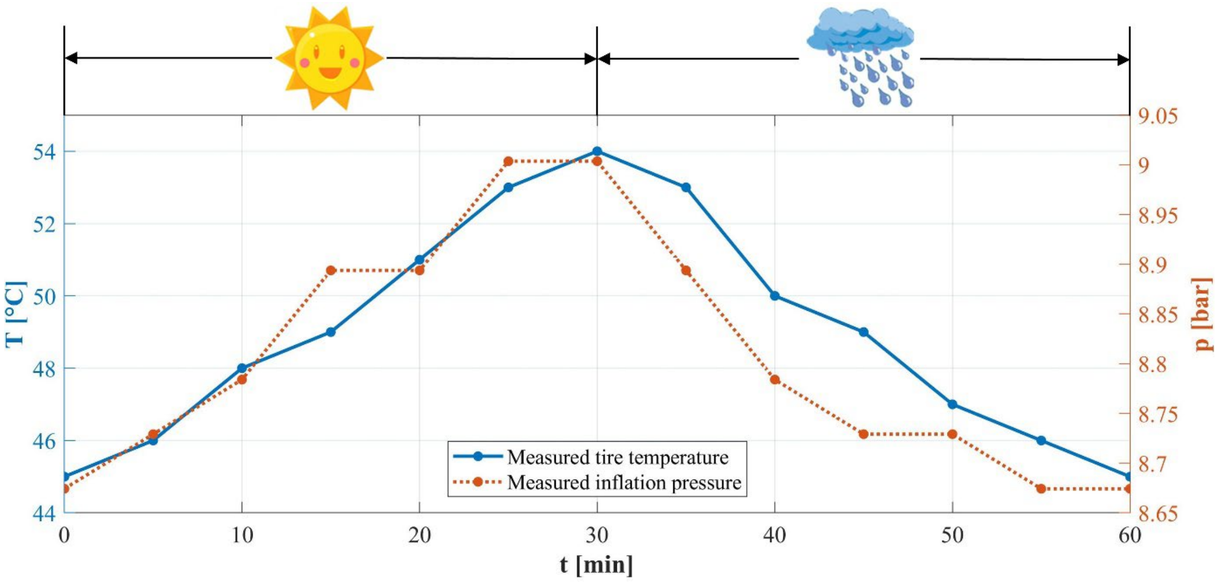



**Figure 8 – Effect of heavy rain on tire pressure and tire temperature during fuel test**

We used these heavy rain conditions to compare the fuel consumption for a duo-trailer combination with 5 lifted axles (T2A6) vs a combination with no lifted axles (T2A11). The rain caused the fuel consumption for T2A6 to increase by around 25 % and by around 23 % for T2A11. Moreover, the fuel consumption decreased by about 10 % when 5 axles were lifted under dry conditions and by approximately 8 % under wet conditions. In conclusion, heavy rain with water on the road has a greater impact on fuel consumption than lifting 5 of 11 axles has. This effect is caused by the fact that water on the road must be pushed aside by the tires, plus the fact that the rain water cools the tires (decreases temperature and pressure build-up), which leads to higher rolling resistance.

**Table 2 – Impact of heavy rain on fuel consumption for duo-trailer combination**

| Vehicle combination | Fuel consumption [l/100 km] | |
|---|---|---|
| *T2A6: 2 semitrailers with 6 axles on the road<br>*T2A11: 2 semitrailers with 11 axles on the road |  |  |
|   | 35 | 44 |
|   | 39 | 48 |

## 3.5. Laboratory rolling-resistance test with a single tire on steel drum

In rolling-resistance tests, the rolling resistance of a tire decreases as the temperature and pressure increase. This chapter clarifies which of these two parameters is more significant.
The effect of tire pressure can be analysed by running two rolling-resistance tests: one with increasing (gradually elevating, as on vehicle) tire pressure and one with maintained (kept at a

constant level) tire pressure. The temperature effect can be analysed by plotting the signal from the rolling-resistance machine over time.
Two different types of truck tire (Tire A and Tire B) were tested on a steel drum at Goodyear's laboratory. Both tires were inflated to 8 bar at 25 °C. The test lasted for about 3 hours with continuous measurement of the rolling resistance. Two different scenarios were tested: Maintenance of a constant pressure (8 bar) and increased pressure as the tire warms up. The plotted graphs are shown in Figure 9. The observed change in rolling resistance between the two curves is less than 2 % for tire A and less than 5 % for tire B. Hence, the data show that the tire temperature has a greater effect on rolling resistance than the tire pressure.

Figure 9 shows the impact of temperature and inflation pressure on rolling resistance for two different tires. The temperature has the greatest impact as stated in point 1 in the conclusion, whereas the influence of inflation pressure on rolling resistance is much lower in this case.

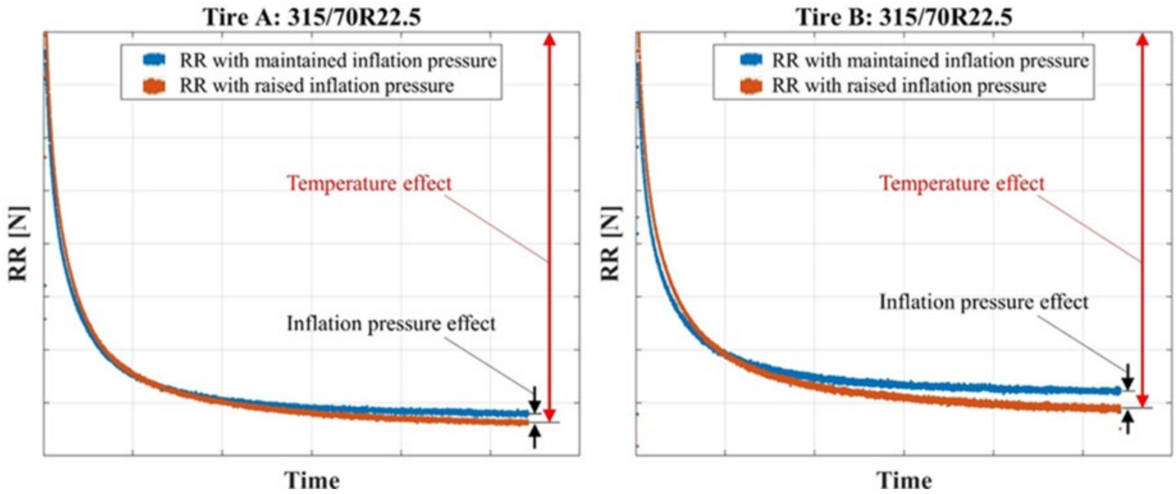


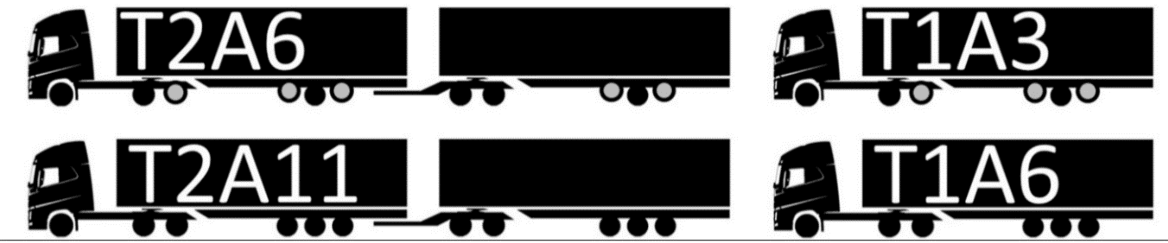

**Figure 9 – Rolling resistance over time for 2 commercial tires, A and B**
**Tire A: Pressure maintained at 8 bar (blue) and increasing up to p=9.36 bar (orange)**
**Tire B: Pressure maintained at 8 bar (blue) and increasing up to p=9.13 bar (orange)**

### 3.6. Comparison of fuel consumption of single-trailer and duo-trailer combinations

This chapter analyses the impact of axle management on fuel consumption for different single-trailer and duo-trailer vehicle combinations. The test was performed with four combinations, as shown in Table 3. The results for fuel consumption, air drag and rolling resistance are also shown in Table 3. Note the significant change in rolling resistance, which is reflected in a substantial reduction in fuel consumption. The reduced rolling-resistance coefficient is calculated as an average for all tires. The reduction of rolling resistance for the tires on the semitrailers and the driving axle is even larger. However, the method used in this study does not allow estimation for specific tire positions.

**Table 3 – Comparison of different trailer combinations at 80 km/h**

| Type | GCW [tonnes] | Axles [#] | Fuel consumption [l/100 km] | $C_d$ [-] | $C_{rr}$ $10^3$ [-] | Fuel reduction [%] | $C_{rr}$ reduction [%] |
|---|---|---|---|---|---|---|---|
| T2A6 (Duo) | 43 | 6 | 32.6 | 0.8 | 4.8 | 8.2 | 14.3 |
| T2A11 (Duo) | 43 | 11 | 35.5 | 0.8 | 5.6 | - (reference) | |
| T1A3 (Single) | 23 | 3 | 24.5 | 0.74 | 5.1 | 3.2 | 7.3 |
| T1A6 (Single) | 23 | 6 | 25.3 | 0.74 | 5.5 | - (reference) | |




The table compares the fuel consumption with some axles lifted to the fuel consumption with no axles lifted. The fuel savings are shown both as litres per 100 km and as percentages. Lifting 5 axles in the duo-trailer combination (T2A6) reduced the fuel consumption by circa 8.2 % and the rolling-resistance coefficient by about 14.3 % when calculated at a constant speed and with constant air drag. Lifting 3 axles in the single-trailer combination (T1A3) reduced the fuel consumption by circa 3.2 % and the rolling-resistance coefficient by about 7.3 %. Furthermore, at 80 km/h the fuel consumption of the duo-trailer combination (T2A11) was about 30 % lower than the combined consumption of two single-trailer combinations (T1A6). When we compared the fuel consumption for combinations with lifted axles (T2A6 vs T1A3), we found that the fuel consumption of the duo-trailer combination was about 33 % lower than the combined consumption of two single-trailer combinations with lifted axles.

### 3.7. Lifting axles in various positions

When lifting axles, there are several functions and features that need to be taken into consideration, the main ones being: axle load, drivability, stability, and maneuverability.
For axle load, the goal is to always have enough load on driving axles and on active steering axles on the truck to ensure that the tractor is able to control the combination, and not the other way around. When driving at high speeds, the active wheelbases of trailers should be as long as possible to maximize the combination stability, while the active wheelbase should be as short as possible for optimum maneuverability at low speeds. When driving with an unloaded truck, as many axles as possible should be lifted, as discussed by "Larsson et al. (2021)" and "Larsson, Pettersson and Fröjd (2018)".

## 4. Discussion

It is a well-known fact that lifting axles decreases the rolling resistance and the rolling-resistance coefficient, which in turn reduces both tire wear and fuel consumption considerably, see "Larsson, Cider and Pettersson (2016)". The absolute values vary from case to case and depend on many factors such as axle load, axle configuration, steering or driving axle, and road conditions.

In this study we have shown that when tires are loaded, they heat up while driving, which in turn increases the tire pressure. The increase in temperature and pressure follows the ideal gas law. Of these two factors, tire temperature is more important than tire pressure for rolling resistance, as shown in chapter 3.5.

The absolute fuel savings presented here are representative for this study. However, the magnitude of the fuel savings is substantial and explained. The new finding is the impact of tire temperature.

### 4.1 Comparison of power usage between single-trailer and duo-trailer combinations

The present experimental study has been made with fixed weights allowing to lift 5 axles on the duo-trailer and 3 on the single-trailer. In typical use cases the weight varies from unloaded up to maximum allow weight. The fuel consumption and power needed is greatly dependent on the weight. Moreover, the weight of the vehicle combination also affects the number of axles that can be lifted. Thereby, again the power and fuel consumption usage. Below we will elaborate on the power usage for the single and duo-trailer at different weights.

The 13-litre engine in the Volvo truck has a power rating of 405 kW. The total power required to drive at 80 km/h on a flat road is around 100 kW. The estimated power needed to pull a more realistic load of 15 tonnes per semitrailer at 80 km/h is shown in Table 4. The rolling-resistance coefficient, $C_{rr}$, is adjusted to reflect the number of axles used. Note that the impact of lifting axles is larger for the duo-trailer combination than for the single-trailer one.

**Table 4 – Estimated power usage with 15-tonne load in each semitrailer**

| Type | GCW [tonnes] | Axles [#] | Mean axle weight [tonnes] | $C_d$ [-] | $C_{rr}$ $10^3$ [-] | $F_{air}$ [N] | $F_{roll}$ [N] | $P_{air}$ [kW] | $P_{roll}$ [kW] |
|---|---|---|---|---|---|---|---|---|---|
| T2A7 | 60 | 7 | 8.6 | 0.8 | 4.9 | 2567 | 2887 | 57 | 64 |
| T2A11 | 60 | 11 | 5.5 | 0.8 | 5.6 | 2567 | 3300 | 57 | 73 |
| T1A4 | 35 | 4 | 8.8 | 0.74 | 5.2 | 2375 | 1787 | 53 | 40 |
| T1A6 | 35 | 6 | 5.8 | 0.74 | 5.5 | 2375 | 1890 | 53 | 42 |

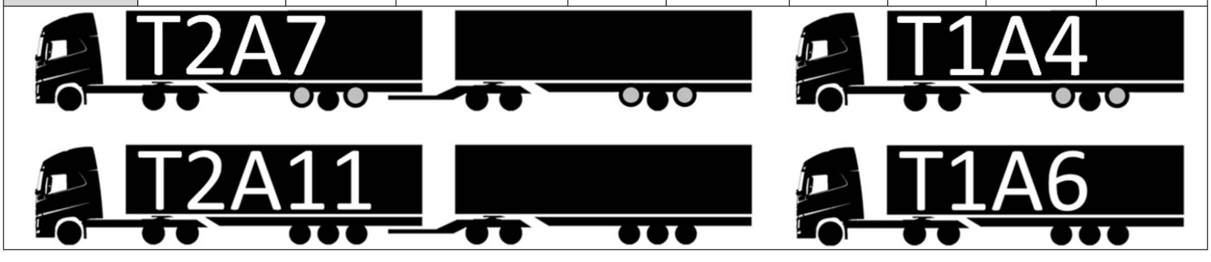



Figure 10 shows the model-based influences of the gross combination weight (GCW) and of lifting axles for a duo-trailer combination, while Figure 11 illustrates the same influences for a single-trailer combination. The model takes the mean axle load into consideration and does not allow a mean axle load that exceeds 9 tonnes. This model could be further refined through additional rolling-resistance measurements with varying GCWs. Nonetheless, the big picture is clear: The influence of rolling resistance on total fuel consumption increases in longer combinations.

In Figure 10, the blue line shows the constant influence of air drag. The orange line shows the rolling resistance with 11 axles on the road, and the dotted yellow line shows the rolling resistance with the maximum number of axles that can be lifted without the average axle load exceeding 9 tonnes. The black dotted line highlights the values for a 60-tonne GCW with four lifted axles versus no lifted axles.

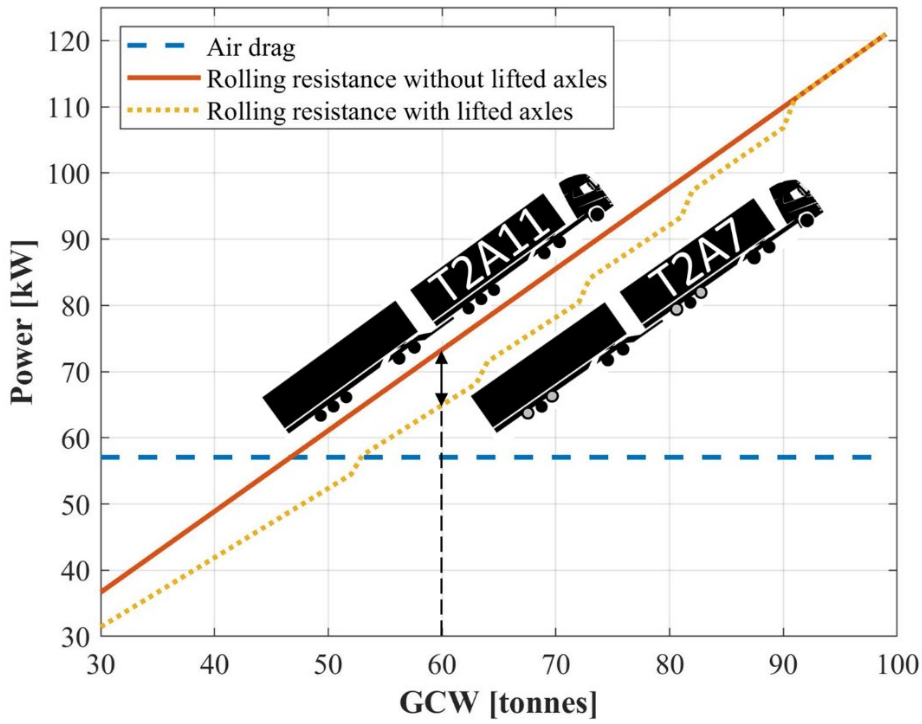



**Figure 10 – Power usage in relation to gross combination weight for a duo-trailer combination at 80 km/h. The black dashed line represents a 15-tonne load in each semitrailer, comparing power usage for 4 lifted axles with no lifted axles.**

Similarly, Figure 11 gives the same data for a single-trailer combination. The blue line is the air drag, which is constant at this speed. The orange line plots the rolling resistance with 6 axles on the road, while the yellow dotted line highlights the rolling resistance with the maximum number of axles that can be lifted without the average axle load exceeding 9 tonnes. As in Figure 10, the black dotted line highlights the values for a 35-tonne GCW with two lifted axles versus no lifted axles.

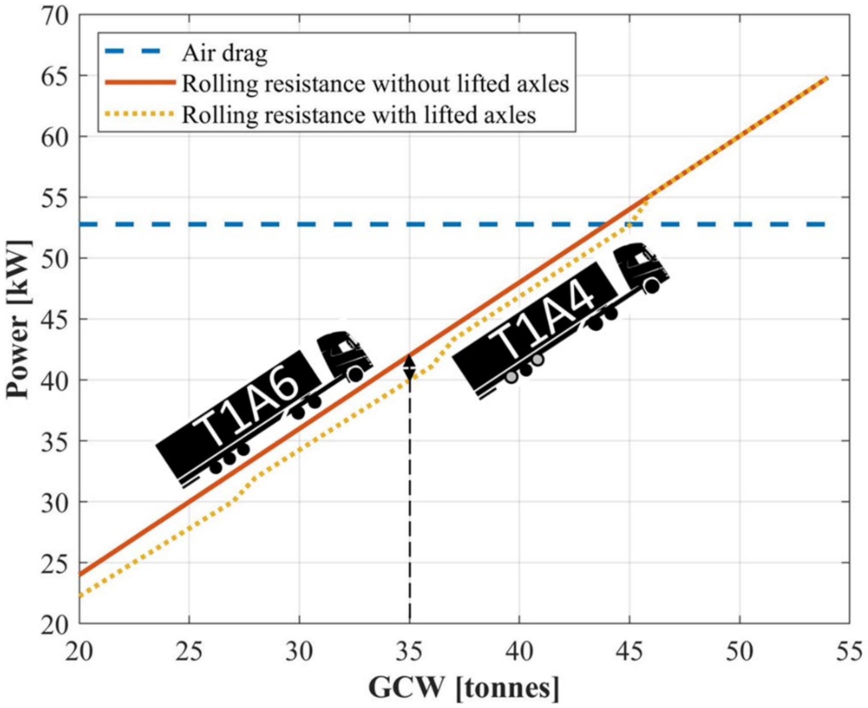



**Figure 11 – Power usage in relation to gross combination weight for a single-trailer combination at 80 km/h. The black dashed line represents a 15-tonne load in the semitrailer, comparing power usage for 2 lifted axles with no lifted axles.**

## 5. Conclusions & recommendations

This article analyses the differences in fuel consumption of several HCT combinations at a constant speed of 80 km/h. The impact of different axle-lifting configurations in single-trailer and a duo-trailer combinations, as well as dry versus wet road conditions were investigated. Sensor-equipped Goodyear tires were used to measure the tire temperature and tire pressure in all of the experiments. Additionally, a force sensor was placed between semitrailer 1 and the dolly to measure the longitudinal forces of the second trailer in different axle configurations. The most significant findings are the following:

- Tire temperature is the property that has the greatest effect on rolling resistance, and it takes about 1 hour to reach a stable tire temperature on the road.
- The longitudinal force measured in the dolly drawbar eye is consistent with the fuel consumption and provides detailed information about the pure rolling resistance of the second trailer, since air drag is significantly smaller.
- Lifting 2 axles in the second trailer reduces fuel consumption by 6 %.
- Lifting 5 of 11 axles in the duo-trailer combination reduces fuel consumption by 8.2 %, while lifting 3 of 6 axles in the single-trailer combination reduces it by 3.2 %.
- Fuel consumption increases by about 25 % in heavy rain with circa 3 cm of water on the road.

Therefore, the following recommendations are defined:

- Axle management combined with control of tire pressure and tire temperature will decrease fuel consumption and improve the handling of a vehicle combination.
- Utilize an HCT combination for your transport. Rolling resistance typically has a higher impact on an HCT combination's fuel economy than air drag does.
- Lift some axles, if possible, to increase the temperature in the tires that are carrying the load by considering appropriate tire load guidelines from the tire manufacturer. This increase in temperature will reduce the total rolling resistance.
- Take vehicle handling into consideration when deciding which axles to lift.

## 6. Acknowledgments

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