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Effects of External Tire Heating on Rolling Resistance Energy Consumption

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Abstract. It is known that the rolling resistance decreases with increasing tire temperature. If the tires could be heated to a high temperature, the rolling resistance's energy loss could be reduced. The question arises whether the reduced rolling resistance energy consumption overcomes the energy required to heat the tire.

This paper investigates the effects of external heating and improved tire insulation theoretically. The results indicate that external tire heating can be beneficial only if the heat used is waste heat, generated from a heat pump or similar with a coefficient of performance greater than one or taken from the grid.

Keywords: Rolling resistance · Tire temperature · Modeling

1 Introduction

Rolling resistance is impacted by the tire temperature mainly through the hysteresis losses that occur during the repeated compression-decompression of the rubber in a rolling tire. This loss energy will end up as heat in the tire. As the tire's temperature increases, the rolling resistance decreases. Rolling resistance is defined as the amount of mechanical energy converted into tire heat for a unit distance, according to [1]. From a tire perspective, this is a convenient definition since tire temperature can be measured and easily quantified. However, from a vehicle energy consumption perspective, this definition is not always adequate since there exist more energy losses related to a rolling vehicle, such as displacement of snow or water on the road, compression of soft road surfaces, and losses in suspension due to road unevenness.

This paper investigates the impact of tire temperature on rolling resistance in general and the potential energy consumption gains from external tire heating in

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particular. To analyze the effect on rolling resistance energy consumption from tire heating, a dynamic model is needed. Nielsen et al., [2], has developed such a model for the rolling resistance. This model uses a function of the tire temperature and a deviation between the current vehicle speed and a steady-state vehicle speed to determine the rolling resistance. The tire temperature is dynamically modeled, with the change rate being linear in the deviation between the current temperature and a steady-state temperature. From [2], it can be deduced that tire temperature is a key parameter for determining rolling resistance. Another interesting finding by [3] is that the shoulder temperature in steady state is close to the inflated air temperature within the tire. In [2], where their model is shown to perform well for tests a given truck in given conditions. This fact is used to motivate only one lumped state to describe the tire temperature. This radically simplifies the model. Furthermore, in [4,5], a relation between rolling resistance and tire temperature is established. However, there are no attempts to investigate if external heating of tires would be beneficial.

The main scope of this paper is to use a simplified dynamic tire temperature and rolling resistance model to investigate the impact of external tire heating and if pre-heating of truck tires can be used to extend vehicle driving range. The rolling resistance models are based on the works of [2,4], and the definition of rolling resistance from [1] is used.

2 Method

2.1 Effects from Tire Heating on Rolling Resistance

The hysteresis loss of a tire, the main contributor to rolling resistance, is highly dependent on the tire temperature. In [4], the rolling resistance coefficient, C_{rr}, is described as being an exponential function of the tire temperature, T_t. The dependency on the vehicle speed, v_v, is described as a shift in T_t while the dependencies on other parameters like tire pressure, P_t, road surface roughness, r_r, and tire wear, W_t, are not explicitly described. In our work, C_{rr} is modeled in the same way, i.e.:

$$C_{rr}(T_t) = c_0 + c_1 e^{-\frac{T_t + \Delta T_t(v_v)}{c_2}}, \tag{1}$$

where c_0, c_1 and c_2 are constant coefficients and

$$\Delta T_t(v) = T_h + (T_0 - T_h)(2 - \frac{2}{1 + e^{-c_3 v_v}}), \tag{2}$$

describes the shift in T_t as a function of v_v, where c_3 is a constant coefficient, T_h the tire temperature shift at infinite vehicle speed, and T_0 the tire temperature shift at zero vehicle speed.

With the chosen definition of rolling resistance, [1], the tire heat power generated by the rolling resistance, P_{rr}, at time t can be described by:

$$P_{rr}(t) = F_z C_{rr}(t) v_v(t), \tag{3}$$

where F_z is the total normal force of all tires, and v_v is the vehicle speed. Since this is the total tire heat generated from the rolling resistance, a dynamic temperature model (similar to [2]) can be developed according to:

$$\frac{dT_t}{dt} = \frac{P_{rr}(t) - P_{diss}(t) + P_{ext}(t)}{m_t c_t}, \tag{4}$$

where P_{diss} is the heat dissipation from the tire to the ambient air, road surface, and rim, m_t is the tire's mass, c_t the heat-specific capacity of the tire material, and P_{ext} is externally added heat power.

Assuming that the rim, the road surface, and the ambient air all have the same temperature, T_a, the heat dissipation can be described as:

$$P_{diss} = c_d(T_t(t) - T_a(t)), \tag{5}$$

where c_d is a coefficient determining the total heat dissipation of the tire.

2.2 Tire Temperature and Rolling Resistance Coefficient over Time

Equations (3), (4) and (5) can be used together with the current tire temperature, $T_t(0)$, to predict the tire temperature going forward, $T_t(t)$:

$$T_t(t) = T_t(0) + \int_0^t \frac{P_{rrh}(\tau) - P_{diss}(\tau) + P_{ext}(\tau)}{m_t c_t} d\tau \tag{6}$$

A possible way of solving (6) is to discretize the problem into N, sufficiently small steps, which gives:

$$T_{t,0} = T_t(0), \tag{7a}$$

$$T_{t,N} = T_t(t), \tag{7b}$$

$$t_s = \frac{t}{N}, \tag{7c}$$

$$T_{t,i+1} = T_{t,i} + t_s \frac{P_{rr}(T_{t,i}) - P_{diss}(T_{t,i}) + P_{ext}(\tau)}{m_t c_t}, \tag{7d}$$

$$T_{t,N} = T_{t,0} + \sum_{i=0}^{N} t_s \frac{P_{rr}(T_{t,i}) - P_{diss}(T_{t,i}) + P_{ext}(\tau)}{m_t c_t}. \tag{7e}$$

Equation (7) can now be used in a forward simulation to predict $T_t(t)$. By inserting $T_t(t)$ into (1), $C_{rr}(t)$ is given which is needed to compute the next value of $P_{rr}(T_{t,i})$. The parameter values used for the rolling resistance coefficients are taken from [4]. All parameter values are given in Table 1.

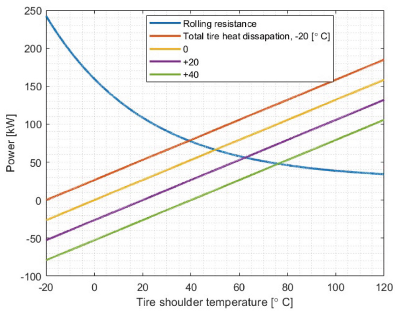
Table 1. Parameter values

Parameter	Value	Parameter	Value	Parameter	Value
c_0	3.09 [kg/ton]	c_1	15.21 [kg/ton]	c_2	0.0243 [$°C^{-1}$]
c_3	0.0232 [h/km]	T_0	69.2 [$°C$]	T_h	-25.7 [$°C$]
m	40000 [kg]	g	9.81 [N/kg]	m_t	600 [kg]
c_t	1880 [$J/(kg°C)$]	c_d	1320 [$W/°C$]		

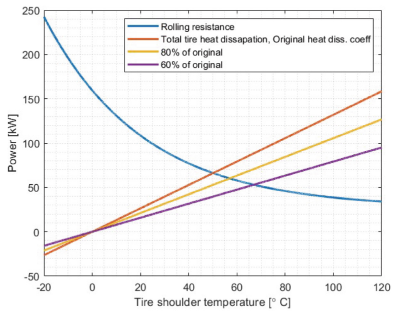
3 Results

In Fig. 1a, the rolling resistance power, $P_{rr}(T_t)$ is plotted towards T_t using Eq. 1 when running in 80 km/h together with heat dissipation power curves for four different ambient temperatures. The crossings between the P_{rr} curve and the heat dissipation curves give the steady-state rolling resistance power and steady-state T_t. This shows that one of the main reasons why rolling resistance tends to increase when the ambient temperature is decreased is that the tires will be colder.

In Fig. 1b, the effect on steady-state rolling resistance from different c_d is shown. It should be noted that a lower c_d gives lower steady-state rolling resistance. This means that running on road material with low heat conductivity, like packed snow, may give lower rolling resistance than running on road material with high heat conductivity. It also means that if tires can be heat insulated, it is likely to result in a significant reduction in P_{rr}.



(a) Rolling resistance and heat dissipation power in different ambient temperatures.



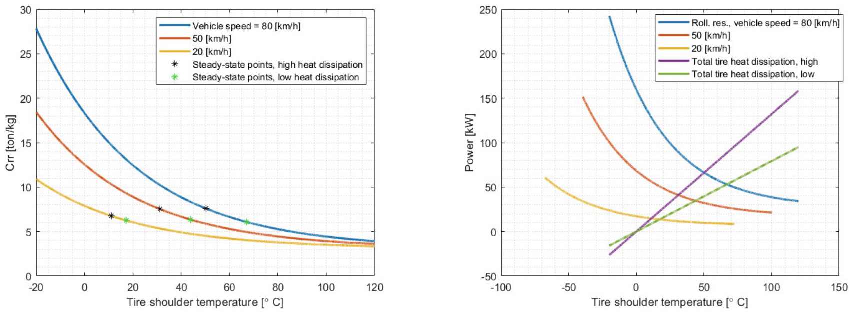
(b) Rolling resistance and heat dissipation power for different heat dissipation coefficients

Fig. 1. Rolling resistance and heat dissipation power.

The vehicle speed dependency in the used model is described as a shift in tire temperature. Figure 2a illustrates how C_{rr} is changing with tire shoulder temperature for three different vehicle speeds. The black stars denote steady-state points when c_d is high, and the green stars do the same thing but when

c_d is low. The speed dependency of rolling resistance in steady-state seems to decrease with decreasing c_d.

In Fig. 2b, C_{rr} as function of T_t is plotted for three different values of v_v together with heat dissipation curves for high and low values of c_p. The dependency on T_t for P_{rr} is reduced with v_v which also means that the impact from c_d on steady-state rolling resistance increases with v_v.



(a) C_{rr} dependency on tire shoulder temperature and vehicle speed

(b) Rolling resistance power for different vehicle speeds

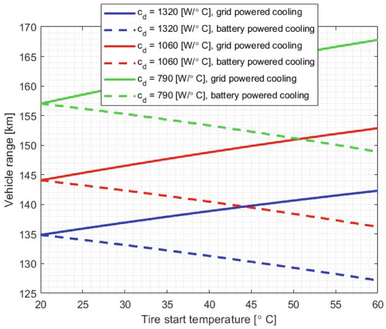
Fig. 2. C_{rr} and rolling resistance power at different vehicle speeds

The total vehicle range is affected by the tire temperature at the start of a trip. If assuming that the vehicle has a total of 100 kWh of battery capacity that is dedicated to rolling resistance energy consumption, the vehicle range can be computed from forward simulations of the rolling resistance energy consumption from (6). In Fig. 3a, the vehicle range for different initial tire temperatures are plotted for three different c_d at $T_a = 20°C$. The solid lines denote the gross effect of tire heating, i.e., the range if the tires are pre-heated using grid energy. The dashed lines denote the net effect, i.e., if the tires are heated using battery energy of the vehicle. As can be seen, vehicle range is always benefiting from pre-heating from the grid. The effect is, however, not so large that it overcomes the loss in the range from using battery energy for the tire heating, which can be seen from the fact that the range for the net curves decreases with tire start temperature. This figure also shows that vehicle range is highly affected by c_d.

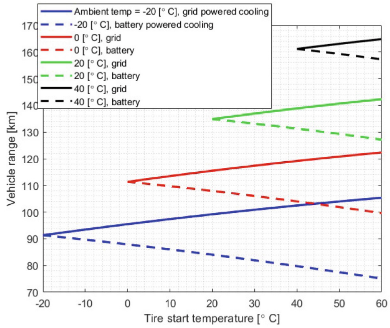
In Fig. 3b, the effect of tire heating at different ambient temperatures is illustrated. The lines are almost parallel, which means that tire pre-heating is likely to be as effective independently of ambient temperature. However, the curves are not completely linear. The vehicle range is growing slightly slower than linear in tire start temperature which means that tire pre-heating will be a little bit less effective for each degree T_t is increased.

4 Discussion and Conclusions

Overall, the benefit of adding external tire heat in terms of decreased rolling resistance energy will always be positive since rolling resistance energy con-



(a) Vehicle range with different heat dissipation coefficients and different initial tire temperatures.



(b) Vehicle range in different ambient temperatures and different initial tire temperatures.

Fig. 3. Vehicle range dependency on initial tire temperature

sumption decreases monotonically with tire temperature. However, the gain in decreased rolling resistance energy consumption from external heating will always be smaller than the amount of external heat needed since some of the external heat will be dissipated to the surroundings. This means that external tire heating will never be beneficial unless the energy used comes from waste heat or is generated from a heat pump with a coefficient of performance greater than one. Tire pre-heating may still be e a good idea when the vehicle is plugged into the grid utilizing cheap electricity or if vehicle range is vital to fulfill a transportation mission. To be able to avoid an extra charging stop is often more valuable than the cost of extra energy needed for tire heating. Note, though, that all computations are based on the assumption that the tires can be heated without any loss in energy, which is unrealistic. Hence, in reality, the dashed lines of Fig. 3 will be pointing even steeper downwards indicating higher total net energy loss.

Tire heating may be beneficial if there is a surplus in electric power, for example, when going downhill with a full battery, if waste heat can be utilized for heating the tires, or if using heat from a heat pump with a sufficiently high coefficient of performance.

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