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Rolling Resistance for a Vehicle when Driving Up and Down a Road Gradient

Lars Nielsen [1)], Mikael Askerdal [2),3)], Fredrik Bruzelius [3)], Carl Emvin [3)], Lars Eriksson [1)], Mattias Hjort [4)], Bengt Jacobson [3)], Mats Jonasson [3)], Sogol Kharrazi [1),4)]

1) Department of Electrical Engineering, Linköping University, Sweden
2) Department of Vehicle Motion and Thermal Management, AB Volvo, Gothenburg, Sweden
3) Department of Mechanical Engineering, Chalmers University, Sweden
4) The Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden
(Corresponding author : lars.nielsen@liu.se)

Abstract: The rolling resistance of a vehicle is important, e.g., for range estimation. The question addressed is how total rolling resistance of a vehicle changes going up or down a hill, with everything else being the same. The basic idea in this paper is that rolling resistance of tires come from energy losses due to tire deformation repeated each wheel revolution. Going uphill requires more driving torque than driving on horizontal road, thus more deformation, more losses, and more rolling resistance. Going downhill is opposite, it requires less driving torque than horizontal road, and thus less deformation, less losses, and less rolling resistance. Based on model discussions, conjectures are made, and an experimental investigation method is proposed. Also based on model discussions, the first question is whether the rolling resistance decreases with per milles going uphill, if the inclination is in the order of percents, or if it increases with percents. An experimental program is suggested and initiated.

Keywords: Vehicle Dynamics, Vehicle Control, Chassis, Automated Driving, Integrated Control

1. Introduction

The standard model for vehicle longitudinal motion is

$$m\dot{v} = F_{\mathrm{d}} - F_{\mathrm{rr}} - F_{\mathrm{a}} - F_{\mathrm{g}} \tag{1}$$

where F_{d} is the driving force from the powertrain, F_{rr} is the total rolling resistance due to deformation losses in the tires, F_{a} is the total air drag on the vehicle, and F_{g} is the gravitational force, see also Appendix A.

This is an important equation used in many studies, e.g. mission simulations and more. In recent years the model has received increased interest due to increased needs for range estimation. The F_{rr} is often modelled as a proportional to the normal force $F_{\mathrm{rr}} = mgC_{\mathrm{rr}}$, and there are detailed studies that investigate the influence on F_{rr} or C_{rr} from speed, road surface structure and softness, tire temperature, etc. The influence of road grade is studied in this paper.

Consider the case of a vehicle cruising on horizontal road, and assume that the model (1) is valid. Assume now that the vehicle enters an uphill or downhill inclination with an angle α where

- $\alpha > 0$ means driving up the grade
- $\alpha < 0$ means driving down the grade

The main question addressed here is how the rolling resistance, F_{rr}, in the vehicle model (1) should be adjusted for this situation. In other words, how the rolling resistance depends on inclination α, i.e., what are the characteristics of the function $F_{\mathrm{rr}}(\alpha)$.

The presentation is organized as follows. The next section gives background on rolling resistance. Section 3 formulates the main question of the paper, where the basis is the assumptions that the longitudinal deformation of the tire is proportional to the longitudinal forces acting on the tire (as predicted by Hooke's generalized law), and that the energy losses are proportional to the deformation. This leads to two different models for rolling resistance in inclinations that both can not be true, and based on that, an experimental program is proposed in Section 4, and initial experiments are presented in Section 5. Further analysis and discussion are provided in Sections 6 and 7, and the conclusions are drawn in Section 8. The main question in this paper is about two conflicting ideas where the details in the equations are not essential, so most of these are put in the appendices last in the paper.

2. Background

Rolling resistance for a wheel on horizontal road is a well studied topic where classical works are [1–3]. More recent surveys can be found in [4,5]. Experiments show, for a wheel on horizontal road, that

$$F_{\mathrm{rr}} = F_{\mathrm{rr,flat}} = mg\, C_{\mathrm{rr}}(T, p, v, \dots), \tag{2}$$

with tire temperature T, tire pressure p, and vehicle speed v. It is worth noting that the gravitational force, mg, is factored out, and is not part of C_{rr}. This can be seen as a reflection of the fact that the deformation of the tire, $\mathcal{D}$, is proportional to the force acting on it, and further, that the energy losses in turn are proportional to the deformation.

The rolling resistance of a free rolling tire is mainly caused by hysteresis losses inside the tire due to tire deformations, while slip in the contact area accounts for 5-10% of the total losses and drag due to air friction a few percent[(1)]. The rolling resistance can in most circumstances be regarded as a force opposing the direction of travel. There are however cases when the force concept can be misleading, and a more general definition of rolling resistance, sometimes referred to a rolling loss has been adopted[(2)]. Then the rolling resistance is defined as "the mechanical energy converted into heat by a tire moving for a unit distance on the roadway". The rolling resistance can then be expressed in input and output power as

$$F_{\mathrm{rr}} = (P_{\mathrm{in}} - P_{\mathrm{out}})/v, \tag{3}$$

where v is the road speed of the tire, P_{in} is the power provided to the wheel from the wheel axle, and P_{out} is the mechanical power

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delivered by the wheel. For a tire without any slip angles or camber angles, this can be rewritten as

$$F_{\mathrm{rr}} = M\omega/v - F_{\mathrm{x}}, \tag{4}$$

where M is the applied torque on the wheel axle, ω is the wheel rotational speed, and F_{x} is the tire longitudinal force. This relation is valid for all cases where the tire is driven, braked or free rolling. Measurements have been conducted over the years to investigate the influence from tractive and braking forces. In general the rolling resistance increases with increased braking or driving forces, while the minimum value often occurs for small driving values leading to a smaller value compared to a free rolling tire. Reduction of slip losses is usually argued to be the cause of this phenomenon. However, it is acknowledged that for some tyres the minimum could occur for small braking forces instead[2]. For a driven or braked tire with moderate longitudinal force, a reduction of the force will then lead to a reduction of the rolling resistance. A recent work[6] has further investigated rolling resistance during brake forces using a specially developed trailer for tire testing that was positioned on a rotating drum, with a specific focus on understanding the actual forces and torques that lead to energy dissipation.

The operating conditions $T, p, v, \ldots$ are important and change C_{rr} significantly [7,8]. The effect of α is expected to be small in comparison, but could nevertheless have an impact for a vehicle where considerable driving forces are needed to negotiate a slope. This is especially so for a heavy vehicle with several undriven axles. The main question of this paper is what $F_{\mathrm{rr}}(\alpha)$ should be in the vehicle model (1), where $F_{\mathrm{rr}}(\alpha)$ is the aggregated total rolling resistance for the vehicle, so it should hold for vehicles with any number of driven wheels, 2WD, 4WD, multiple axles, and so on.

3. Main question addressed

This section introduces the treatment of the main question on how the vehicle rolling resistance $F_{\mathrm{rr}}(\alpha)$ depends on α. For a horizontal road $\alpha = 0$, so the rolling resistance is governed by (2) and

$$F_{\mathrm{rr}}(0) = F_{\mathrm{rr,flat}} \tag{5}$$

The initial treatment of $\alpha \neq 0$ will be done in two steps. First, a pulled vehicle is treated in the next section, and then a driven vehicle in the section thereafter. For simplicity, we start with a one-wheeler.

3.1. A pulled vehicle

The case of a pulled one-wheel vehicle is well known, and is usually written as

$$F_{\mathrm{rr}}(\alpha) = \cos\alpha F_{\mathrm{rr,flat}} = \cos\alpha\, mgC_{\mathrm{rr}} \tag{6}$$

To our knowledge there is no careful experimental verification of this in the existing literature, as it is for many other parameters in (2), like $(T, p, v, \ldots)$ where there is a rich literature.

Instead there is a reasoning that is interesting to follow. Recall that the force is factored out in (2), and it is well documented in experiments on horizontal road that the rolling resistance is proportional to the force, mg. On a grade, the normal force is decreased by a factor $\cos\alpha$, and for a pulled vehicle other forces are neglected, even though the deformation could be slightly different, the pressure distribution in the contact patch could be slightly different, and so on. Neglecting these minor differences, the normal force mg is replaced by $mg\cos\alpha$ causing the deformation $\mathcal{D}$ that is repeated each revolution of the wheel. Now there are two steps in the reasoning. The first is that the deformation $\mathcal{D}$ of the tire is proportional to the force, and the second is that energy losses are proportional to the deformation $\mathcal{D}$. If both these assumptions are valid, then the well-known equation (2) follows.

In our treatment of a vehicle creating its own propulsion we will follow the type of argumentation above. For that purpose, we introduce a compensation factor γ_{ud} where the subscript "ud" stands for up and down. Then (6) can be written as

$$F_{\mathrm{rr}}(\alpha) = \gamma_{\mathrm{ud}}(\alpha)F_{\mathrm{rr,flat}}, \tag{7}$$

with $\gamma_{\mathrm{ud}}(\alpha) = \cos\alpha$ for a pulled vehicle.

3.2. A one-wheel driven vehicle

We now turn our attention to a vehicle with its own propulsion, and we start with a one-wheel vehicle. Just from rolling on a horizontal road, the tire is deformed in the direction of travel as schematically illustrated by Fig. 1.15 in [3]. Overcoming aerodynamic drag and the other terms in (1) adds more deformation.

Assume stationary driving at constant speed ($\dot{v} = 0$), where the tire is repeatedly deformed each revolution of the wheel. The question is then how the deformation changes when going up or down a hill. For this, assume that the total air drag F_{a} is unchanged in (1), and that the gravitational force becomes $F_{\mathrm{g}} = mg\sin\alpha$. This longitudinal gravitational force will shear the rubber of the tire, so that deformation increases going uphill, but decreases going downhill. This is schematically illustrated by Δe in Fig. 3. The first conjecture follows immediately:

Conjecture 1: Compared to rolling resistance on horizontal road, rolling resistance is lower going down, and higher going up, everything else equal.

When formulating this conjecture mathematically we follow the convention from a pulled wheel by describing it as a factor γ_{ud} capturing how the tire force changes. This has also the clear advantage that all knowledge from horizontal road in (2) can still be used without modification. Thus, in

$$F_{\mathrm{rr}}(\alpha) = \gamma_{\mathrm{ud}}(\alpha)F_{\mathrm{rr,flat}}, \tag{8}$$

for a driven vehicle, the factor γ_{ud} obeys

Conjecture 1b: With everything else equal, then

- $\gamma_{\mathrm{ud}} > 1$ going up a grade
- $\gamma_{\mathrm{ud}} < 1$ going down a grade

The next step is to investigate possible functional expressions and quantifications of γ_{ud}. To get a first approximate description, the line of reasoning that was used for a pulled wheel is used also here. The forces on the deformed part of the tire in contact with the road changes when in an inclination. The force normal to the road decreases by a factor $\cos\alpha$ and the shearing force in the longitudinal direction of the road is changed proportional to $mg\sin\alpha$. As for the pulled wheel, neglecting small effects and assuming deformation proportional to deformation forces, then the *change* in deformation, $\Delta\mathcal{D}$, is proportional to $\cos\alpha\sin\alpha$. Then, with the same assumptions as for the pulled wheel, the change in energy losses per revolution is proportional to $\cos\alpha\sin\alpha$, and so is the change in rolling resistance. Introduce the proportionality constant, κ, for the change in rolling resistance. Then, the conjectures for (8) are as follows

Conjecture 2: At least within limits of Hooke's general law,

$$\gamma_{\mathrm{ud}} = \cos\alpha(1 + \kappa\sin\alpha). \tag{9}$$

or

Conjecture 2b: For small α it is $\gamma_{\mathrm{ud}} = 1 + \kappa\alpha$.

A derivation based on force balance in Appendix A leads to the same result. See Fig. 3 for definition of variables used. For

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a viscoelastic wheel, the non-uniform stress distribution shifts the point of application of the normal force N forward by a distance e, giving rise to rolling resistance. On a flat surface, this rolling resistance is

$$F_{\mathrm{rr,flat}} = \frac{Ne}{R} = \frac{mge}{R}.$$

For a driven wheel on an incline, an additional driving force F is required to overcome the component of gravity acting along the slope. This introduces an extra shift Δe. As a result, the rolling resistance becomes

$$F_{\mathrm{rr}} = \frac{N(e+\Delta e)}{R}.$$

Assuming linear elastic behavior, Δe can be estimated using Hooke's law based on the driving force and the longitudinal stiffness of the rubber, C_x. Substituting this into the expression above results in

$$F_{\mathrm{rr}} = \frac{mg\cos\alpha\left(e+\frac{mg\sin\alpha}{C_x}\right)}{R} = \frac{mge}{R}\cos\alpha\left(1+\frac{mg}{C_x e}\sin\alpha\right).$$

Replacing $\frac{mge}{R}$ with $F_{\mathrm{rr,flat}}$ and defining $\kappa = \frac{mg}{C_x e}$, this expression simplifies to

$$F_{\mathrm{rr}} = F_{\mathrm{rr,flat}}\cos\alpha\,(1+\kappa\sin\alpha)\,,$$

and thus $\gamma_{\mathrm{ud}} = \cos\alpha\,(1+\kappa\sin\alpha)$, which is the same as (9).

3.3. A Driven Vehicle

For a vehicle (with more than one wheel), all wheels together carry the weight of the vehicle, and in a grade they have, along the road, to collectively balance the force $F = mg\sin\alpha$ that deforms the rubber. On the other hand the normal force is decreased by $\cos\alpha$ so the deformation of all the tires together, $\mathcal{D}$, is proportional to the same correction factor $\gamma_{\mathrm{ud}} = \cos\alpha(1+\kappa\sin\alpha)$ as for a one-wheel vehicle. Thus, the conjectures for a multi-wheel vehicle are the same as for a one-wheel vehicle.

4. Experimental Program

We are proposing an experimental program, where the first step is the experiment sketched in Fig. 1. The setting is as follows. A vehicle is equipped to measure and/or estimate F_{d}, F_{a}, and F_{g}. At the test track, with known uphills and downhills, the vehicle is driven at constant speed which means $\dot{v} = 0$. Then the vehicle model (1) can be rewritten as

$$F_{\mathrm{rr}} = F_{\mathrm{d}} - F_{\mathrm{a}} - F_{\mathrm{g}} \tag{10}$$

where F_{rr} can be computed from the measured and estimated values on the right-hand side. When driving on a horizontal road, (10) gives $F_{\mathrm{rr,flat}}$. When in an inclination, (10) gives F_{rr}, that then can be plotted relative to $F_{\mathrm{rr,flat}}$ for a comparison as in Fig. 1. If measurements are good enough, then one will be able to discriminate between the two hypotheses of whether $\gamma_{\mathrm{ud}} = \cos\alpha$ is valid also for a driven vehicle, or if Conjecture 1b is a better description. Further, the experimental program will strive for finding out as much as possible of γ as function of α.

4.1. Some Numbers

Some numbers are given to get a feel for what could be expected in experiments, depending on which hypothesis that is correct. The basic observation is that the sine function changes much more than the cosine function for small α.

Trying to determine κ experimentally will be exciting, but κ should depend on the relative stiffnesses of the local deformations of the tire. A perfectly isotropic tire with the same stiffnesses in all directions would have $\kappa = 1$. Of course, a tire is not isotropic, but it would not be surprising if κ is in the order of 1. So, as an example, assume for simplicity $\kappa = 1$ and consider an inclination of 10%, which is steep for normal driving. Then $\alpha = \arctan(0.1)$. For this angle we have

$$\cos\alpha = \cos(\arctan(0.1)) = 0.995\ldots$$

Thus, even for an inclination of this size, the change would be less than 5 per milles.

Consider instead γ_{ud} from (9):

$$\cos\alpha(1+\kappa\sin\alpha) = 0.995(1+\sin\arctan(0.1)) = 1.094\ldots,$$

which means that the change of the factor is almost 10%.

Hence, if the vehicle rolling resistance is governed by $\cos\alpha$ in (1) and (8) then the change would be in order of some per milles, and would hardly be noticeable even for an inclination of 10%. If instead it is governed by Conjecture 2, then it would not be surprising if the change in rolling resistance is much larger, and in the order of the size of the inclination, i.e., several percents. This difference in size is depicted in Fig. 1 by having the changes for the hypothesis of $\cos\alpha$ smaller than for our conjectures.

5. Experiments

First experiments have been initiated together with Volvo and the Revere Lab, and the vehicle used is seen in Fig. 2. The truck is a BEV vehicle with mass $m = 14940$ kg, with two drive axles with the same axle pressure on both. More specifications and parameters of the vehicle are presented in Appendix B as seen in Fig. 4, together with the model equations to be used for analysis.

Main measurements are:

- Signals from vehicle production CAN (e.g. engine torque) and
- Signals from an inertial sensor system RT3000 (e.g. longitudinal acceleration and estimated pitch angle of ground)

The torque measurement is an estimation of the output from the electrical machine with quantization steps of 40 Nm that needs to be handled. The grade sensor for road inclination is mounted on the chassis, so one needs to handle possible offsets from the mounting, but also chassis movements. First experiments were performed in Arjeplog earlier this year, but in that case packed snow was a complicating factor. Nevertheless, even though uncertain. in those experiments, rolling resistance increased by percents going uphill. A new set of experiments were made driving on cruise control (10 km/h) in a long uphill with some variations in grade. It was approximately 1 km road with asphalt on Härkeshultsvägen in Jonsered, and the analysis is in progress. Next step is to obtain and analyze data for cruising speeds, which is the most interesting for range estimation, say 50-90 km/h.

6. Non-linear model

A linear spring is according to Hooke's law modelled as

$$F = \kappa\Delta x,$$

where Δx is the deformation. When Δx becomes large, then a common model is

$$F = \kappa\Delta x + \kappa_3\Delta x^3,$$

reflecting that it requires more force than proportional to create a certain deformation.

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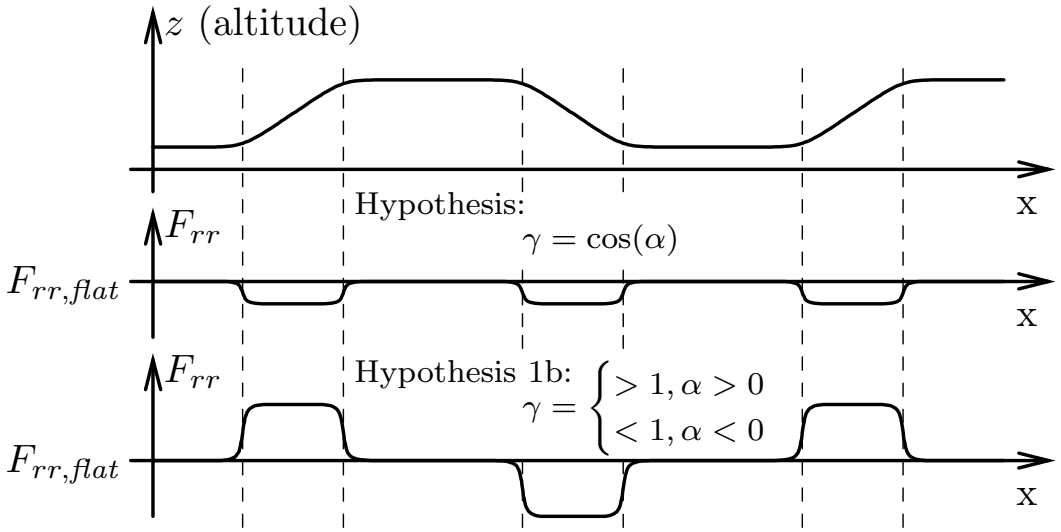

Fig. 1: The top plot is a schematic illustration of a road profile with uphills and downhills. The middle and bottom are schematic illustrations of the change of the vehicle rolling resistance F_{rr} in relation to $F_{\text{rr,flat}}$ according to the two different models. The middle plot shows the characteristics if $\gamma_{\text{ud}} = \cos\alpha$. The rolling resistance of the vehicle would decrease for both uphills and downhills. The bottom plot shows the principle behavior if the rolling resistance of the vehicle increases in uphills and decreases in downhills as in Conjecture 1b.

Fig. 2: The truck used for the experiments.

Similar reasoning can be done for the change of deformation of a tire, $\Delta\mathcal{D}$, when going up or down an inclination. Recall that

$$\Delta\mathcal{D} \propto \cos\alpha \sin\alpha$$

For the linear case, (9) was obtained as

$$\gamma_{\text{ud}} = \cos\alpha + \tilde{\kappa}\Delta\mathcal{D} = \cos\alpha\,(1 + \kappa\sin\alpha)\,.$$

The corresponding non-linear version would be

$$\gamma_{\text{ud}} = \cos\alpha + \tilde{\kappa}\Delta\mathcal{D} + \tilde{\kappa}_3(\Delta\mathcal{D})^3,$$

leading to the following non-linear version of (9):

$$\gamma_{\text{ud}} = \cos\alpha(1 + \kappa\sin\alpha + \kappa_3(\sin\alpha)^3). \tag{11}$$

Both (9) and (11) are non-linear. Interestingly, (9) grows less than linear, but (11) grows more than linear.

If possible, it would be interesting to see what experiments show for this.

7. Discussion

The vehicle model (1) is important in many applications, especially in range estimation, and hence the vehicle rolling resistance, F_{rr}, needs to be modeled. It is not the parameter with the largest effect, but γ_{ud} is needed for best precision. This is important, but perhaps even more so, is the fact that when estimating parameters in model (1) for a specific vehicle, systematic errors in model structure can, even if they are small, cause problems. Here, specifically, there is a risk of underestimating F_{rr} if $\gamma_{\text{ud}} = \cos\alpha$ is used.

8. Conclusions

A new model has been proposed for the change in rolling resistance when going up or down an inclination. Some advantages of the model are:

- it aims for the vehicle model (1) so it can be directly used for, e.g., range estimation.
- the line of physics-based argumentation leading to the conjectures is the same as is well established for a pulled vehicle.
- it is a correction factor γ_{ud} so all the modeling efforts that have been invested in $F_{\text{rr,flat}}$ in (2) is readily available and can be used without modification.

A contribution is the suggestion of an experimental idea that can distinguish between two conflicting hypotheses. Such an experiment has been initiated, and ongoing work is concentrated on refining the experiment and analysing the collected data. It will be exciting to see whether this can confirm our hypotheses, and what the size of κ is for different vehicles and tires, and whether $\gamma(\alpha)$ is reasonably linear or if non-linearities are essential.

9. Acknowledgments

Fredrik von Corswant and Daniel Poveda Pi have been instrumental for the experimental truck, which is highly appreciated.

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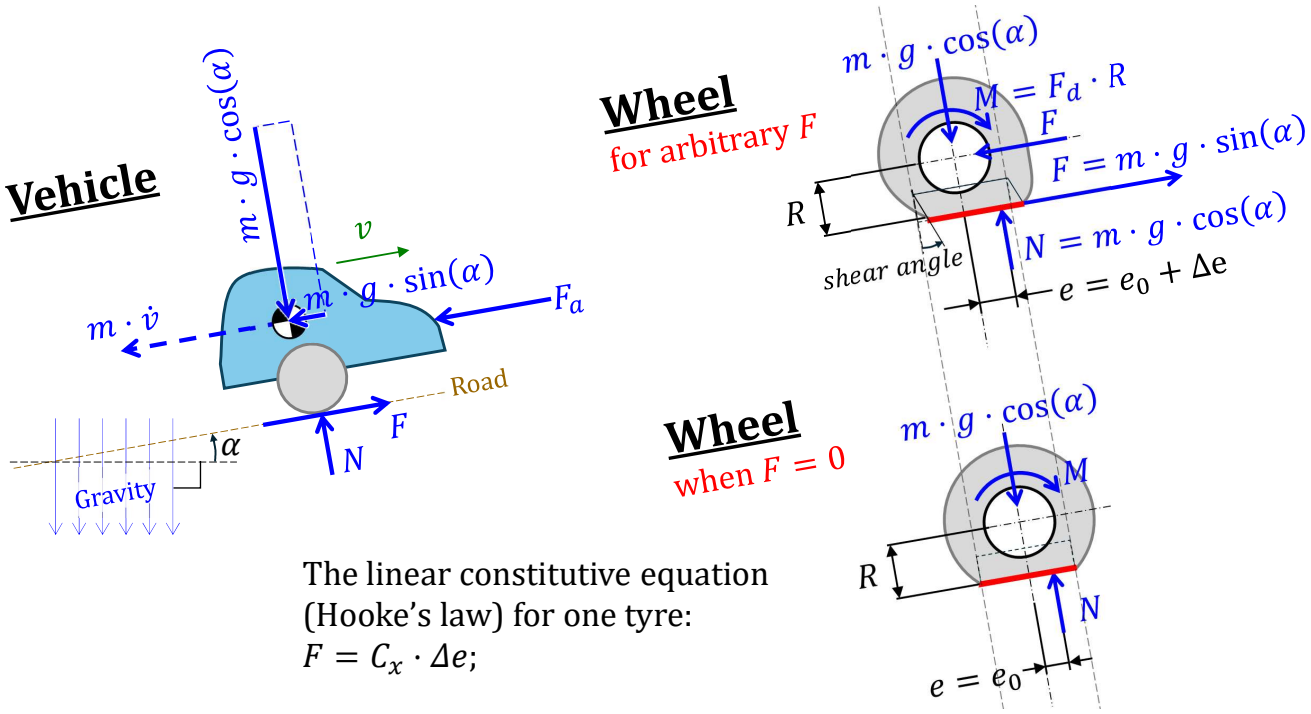

Fig. 3: Equations for a one-wheel vehicle. The main idea is that, in contrast to a pulled wheel, a driven wheel must balance $mg \sin \alpha$. This creates an offset Δe that is positive going up a grade, and negative going down a grade.

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Appendix A: Modeling a one-wheel vehicle in an inclination

The preliminary treatment in Section 3 was based on deformations in the spirit of Schuring. Here model equations will be given in the spirit of Clark using force balances as shown in Fig. 3. The main idea is shown in the upper right. The additional force in the longitudinal direction, $mg \sin \alpha$, creates an additional displacement, Δe, which is proportional to $\sin \alpha$. The derivation was presented in Section 3 directly after Conjecture 2b.

Appendix B: Model of Experimental Truck

The configuration of the experimental truck is presented in Fig. 4, together with main parameters and model equations.

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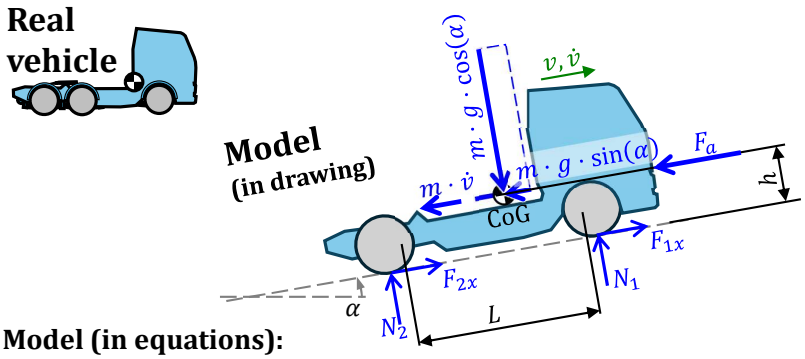

Model (in equations):

//Propulsion system (Friction braking system can be added):

$M_1 = 0$ "undriven front axle";

$M_2 = \{logged\ motor\ torque\} \cdot ratio \cdot \eta - \Delta M$ "driven rear axle";

//Force and moment equilibria for vehicle:

$$m \cdot \dot{v} = F_{1x} + F_{2x} - m \cdot g \cdot \sin(\alpha) - \frac{\rho \cdot A \cdot c_d}{2} \cdot (v - v_{wind})^2;$$

$$m \cdot g \cdot \cos(\alpha) \cdot (L - l_f) - (F_{1x} + F_{2x}) \cdot h - N_1 \cdot L = 0;$$

$$N_2 \cdot L - m \cdot g \cdot \cos(\alpha) \cdot l_f - (F_{1x} + F_{2x}) \cdot h = 0;$$

//Moment equilibrium for wheels on each axle:

$M_1 = F_{1x} \cdot R + N_1 \cdot C_{rr1} \cdot R;$ $\quad M_2 = F_{2x} \cdot R + N_2 \cdot C_{rr2} \cdot R;$

Used parameter values:

- Transmission ratio after shaft where propulsion torque was measured: $ratio$;
- Torque efficiency through the same transmission: η;
- Vehicle gross weight: $m = 14940\ kg$;
- Wheelbase: L;
- Distance from front axle to centre of gravity: l_f;
- Centre of gravity height: h;
- Aerodynamic resistance : $\frac{\rho \cdot A \cdot c_d}{2}$

Fig. 4: Characteristics of the truck for the experiments.

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