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Calculations of Performance Losses for Automobile Vehicles

F. SZODRAI[1], S. PÁLINKÁS[2], GY. JUHÁSZ[3]

[1]University of Debrecen, Faculty of Engineering, Department of Building Services and Building Engineering, szodrai@eng.unideb.hu
[2]University of Debrecen, Faculty of Engineering, Department of Mechanical Engineering, palinkassandor@eng.unideb.hu
[3]University of Debrecen, Faculty of Engineering, Department of Mechanical Engineering, juhasz@eng.unideb.hu

Abstract: Vehicle-energetic-models are used to analyze the performances and when a comprehensive structure is established even optimization could be done. For these kinds of models, the losses of the vehicles have to be known. These losses could significantly effect of the vehicle fuel consumption. From these losses the rolling resistance, drive elements and aerodynamic drag are discussed. This paper reviews some of the literatures that describes the calculation methods and gives us some idea about the degree of their value. Our further goals are to have an UpToDate loss coefficient dataset and calculation methods for further vehicle-energetic-modelling.

Introduction

Approximately half of the mechanical energy generated by the engine of vehicles are devoted to losses of the vehicle. These losses are aerodynamic drag, rolling resistance, losses of drive elements and other collateral losses. Let us assume that if the tires were ideal and the vehicle would be driven in vacuum, only half of the mechanical work would be needed. Additionally, the vehicle would consume less fuel and could travel far longer. On Figure 1. [1] the major losses are distributed to minor sources, by seeing the base and targeted magnitude of the energy losses it clear that the further examinations of the reduction of the losses are crucial. [1,2]

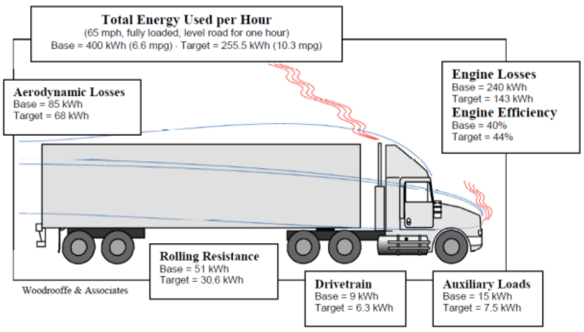

Figure 1. Losses of a truck travelling at 65 mph [1]

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1. Rolling resistance

When the tire rolls on the road, as a result of a phenomenon called rolling resistance, mechanical energy dissipates into heat. In fact, the tire consumes some of the energy passed to the wheels, leaving less energy for the vehicle to move forward. Rolling resistance could increase the vehicle's fuel consumption.

The factors that influences the rolling resistance are: the structure; the material; pattern and size of the tire, temperature and pressure of the air in the tire; speed and weight of the vehicle and the tire slip. Several researches [3-5] are focused on determining the above factors. Figure 2. shows the relation between the temperature the tire drag and journey travelled. Figure 3. shows the change in rolling resistance depending on speed in the case of different structural designs (radial, diagonal, belt diagonal).

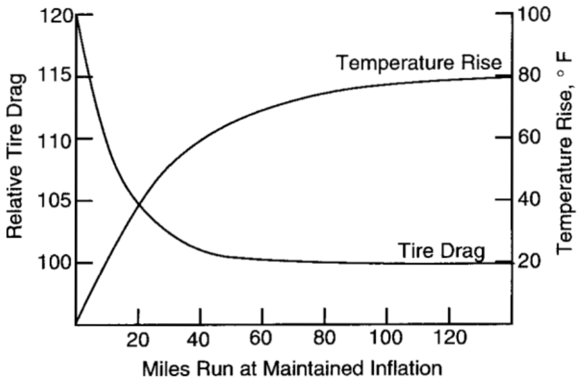

Figure 2. Change in tyre temperature and rolling drag during heating [6]

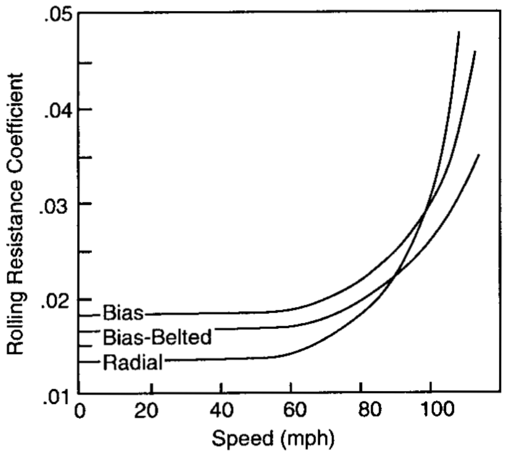

Figure 3. Change in rolling resistance for tyres of different structural designs [6]

The material and thickness of the tire's sidewall and tread determine the tire stiffness and thus the loss of energy that awakens. Figure 4. shows the rolling resistance of experimental tires with different materials with tread and sidewalls.

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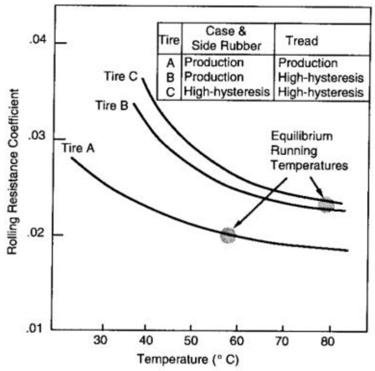

Figure 4. Rolling resistance of tires of different materials in function of temperature [7]

Several equations have been developed for estimating rolling resistance over the years. Studies on the rolling loss (f_r) characteristics of solid rubber tires led to an equation of the form [7]:

$$\boldsymbol{f_r = \frac{R_x}{W} = C \cdot \frac{W}{D} \cdot \sqrt{\frac{h_t}{w}}} \tag{1}$$

where: R_x= Rolling resistance force,

- W= Weight on the wheel,
- C = Constant reflecting loss and elastic characteristics of the tire material,
- D = Outside diameter,
- h_t= Tire section height,
- w = Tire section width.

From this formulation, rolling resistance is seen to be load sensitive, increasing linearly with load. Larger tires reduce rolling resistance, as do low aspect ratios (h_t/w). Some confirmation of the general trends from this equation appear in the literature from studies of the rolling resistance of conventional passenger car tires of different sizes under the same load conditions. Other equations for the rolling resistance coefficient for passenger car tires rolling on concrete surfaces have been developed. The variables in these equations are usually inflation pressure, speed and load. The accuracy of a calculation is naturally limited by the influence of factors that are neglected. At the most elementary level, the rolling resistance coefficient may be estimated as a constant. The table 1. below lists some typical values that might be used in that case. [7].

	Surface		
Vehicle Type	Concrete	Medium Hard	Sand
Passenger cars	0.015	0.08	0.30
Heavy trucks	0.012	0.06	0.25
Tractors	0.02	0.04	0.20

Table 1. Example values for rolling resistances [7]

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2. Drive elements losses

Losses in vehicle propulsion are significantly less than losses from operation of engine aerodynamic drag and rolling drag. In the case of the mentioned truck in the introduction [1], this is only 2%, but many researchers [8-10] are still involved in detecting these losses.

Figure 1. represents the block scheme of the connection between the engine and the wheel where the efficiencies and the losses are highlighted.

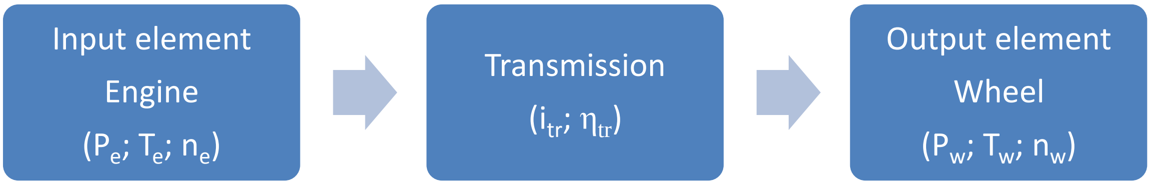

Figure 5. Block scheme of the drive system [11]

On the figure 1. i_{tr} is the transmission of the drive system and η_{tr} is the efficiency of the engine. The i_{tr} is the ratio of the angular velocity of the engine (n_e) and the wheel (n_w) and the efficiency of the engine is the ratio of the power at the wheel (P_w) and the engine (P_e).

Polák et. al. [11] defines the following losses in the engine: tooth friction loss (P_{tf}); bearing loss (P_b); lubricant mixing losses (P_l); air-stirring losses (P_{as}); friction losses of seals (P_{sf}); loss due to rigid deformation (P_d) of components.

2.1. Tooth friction losses

Most of the losses of the gear drive generated by the tooth friction. Various [12] methods have been implemented for its calculation. The tooth friction factor (μ_z) has a major role in the determination of the magnitude of this friction loss, which has a numerous of recommendations to determine. In practice, usually and averaged tooth friction factor is known.

Calculation of the efficiency of the gear drive is the following equation 2, if the geometric size of the gears is known (if part switch numbers (ε) less than 1) [6]:

$$\boldsymbol{\eta = 1 - \pi \cdot \mu_z \cdot (1 - \varepsilon_1 + \varepsilon_1^2 - \varepsilon_2 + \varepsilon_2^2) \cdot \left(\frac{1}{z_1} \mp \frac{1}{z_2}\right)} \qquad (2)$$

In equation 2. z_1 and z_2 the small and large gear number respectively (the + sign is external-external, the - sign is valid for external-external gear connection)

According to Niemann [13] this can be expressed by the following:

$$\boldsymbol{\eta = 1 - 2.1 \cdot \mu_z \cdot \left(\frac{1}{z_1} \mp \frac{1}{z_2}\right)} \qquad (3)$$

in the equation it is assumed that, if sum of ε_1 and ε_2 is between 1.4 and 1.8. the difference will be less than 10% from the measurement.

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2.2. Bearing friction losses

Many researchers [13-15] have been involved in determination of bearing friction losses, although nowadays the manufacturers recommendations are applied [16]. Knowing that the value of bearing losses is very small and difficult to measure, this loss is often disregarded in calculations.

2.3. Lubricant mixing losses

The rotation of the gears that are immersed in lubricant increases engine losses. The calculation of these losses is difficult due to complex flow conditions. Despite this, many researchers have addressed the issue. According to Niemann [9], the oil mixing loss can be approximately determined by the following context:

$$\boldsymbol{P_l = \left(2.72 \cdot 10^6\right)^{-1} \cdot b \cdot b_m \cdot \nu^{\frac{3}{2}}} \tag{4}$$

Where: b is the width of the gear; b_m is the depth of gear immersed in oil and the ν is the kinematic viscosity of the lubricant.

2.4. Losses caused by air-stirring

The loss from air swirling mainly occurs in high-speed engines. As a result of the rotation, the oil that stuck to the gear is detached and creates an oil mist. This oil fog that lubricates the engine elements, also causes performance losses. It is known that this loss is independent from the transferred toque [17].

$$\boldsymbol{P_{as} = 2.82 \cdot 10^{-4} \cdot \left(1 + 4.6 \cdot \frac{b}{d_i}\right) \cdot n_a^{2.8} \left(\frac{d_i}{2}\right)^{4.6} \cdot \left(28 \cdot 10^{-6} \cdot \eta_0 + 0.019\right)^{0.2}} \tag{5}$$

Where: d_i is the gear splitter diameter; n_a is the angular velocity and η_0 is the dynamic viscosity.

2.5. Seal friction losses

Seals on the axles of engines cause torque loss during drive. These losses are independent of the torque transferred. Their value depends primarily on the design of the seal (nominal diameter d_s), the characteristics of the surfaces in contact with the seal, the lubrication conditions and the temperature. Its determination belongs to the field of tribology. In practice simple approximations are enough. An example for its loss calculation is the following: [18]

$$\boldsymbol{P_{sf} = 7.69 \cdot 10^{-6} \cdot d_s \cdot n_a} \tag{6}$$

3. Aerodynamic resistance

Drag is the force that acting on a body that due to the flow around the body or the body that is moving. The drag force (F_D) is proportional to the relative movement of the fluid. For vehicles the aerodynamic

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drag loss is caused by the movement of the vehicle in x direction. For automobile vehicles the magnitude can be corrected with the acceleration (a) and the θ road inclination. The corrected drag force (F_D*) can be expressed:[19]

$$\boldsymbol{F_D}^* = \boldsymbol{m \cdot a + m \cdot g \cdot sin\theta + F_D} \qquad (7)$$

Further corrections can be made if the wind the wind speed is known. Gusts with larger magnitude are not that frequent that it requires to be taken in account. With the following expression (8) if the wind speed is known at the direction of the movement of the vehicle the relative flow velocity (v_x) can be calculated [19].

$$\boldsymbol{v_x = v_{x\,vehicle} - v_{x\,wind}} \qquad (8)$$

The drag could have different magnitude in various fluids, since this paper focuses on automobiles the fluid is air, which density can be calculated dynamically if the ambient pressure and temperature is known at the location of the examination.

$$\boldsymbol{\rho = p_a \cdot (R_{air} \cdot T)^{-1}} \qquad (9)$$

However, the mentioned correction for steady state analysis often ignored due to the negligible fluctuations of the ambient pressure and the temperature, the air density can be considered to be constant also the wind speed can be 0 m s^{-1}. Knowing the velocity and the density of the fluid the dynamic pressure can be calculated. Dividing the drag force with the dynamic pressure and a surface area the drag coefficient can be achieved:

$$\boldsymbol{C_D = F_D \cdot \left(A_x \cdot 0.5 \cdot \rho \cdot {v_x}^2\right)^{-1}} \qquad (10)$$

This A_x surface is the area of the body projected on a normal to the flow direction frontal. When drag coefficient is used the A area has to be clearly defined to make correct verification or validations. For energetic point of view the drag loss is the important coefficient. The lift coefficient that is perpendicular to the movement direction (x) does not have direct effect on the aerodynamic losses. The lift coefficient can tell how much the flow pushes up or down the automobile relative to the ground. When this is known the rolling drag can be calculated, which is a correction factor of the tire deformation and the contact materials. [20]

The pressure coefficient is the ratio of the static pressure difference between the free flow and the surface of the body divided by the dynamic pressure. The pressure drag or Pressure coefficient (C_P) expresses the is the ratio of the static pressure difference and the dynamic pressure. The static pressure difference is measured between the object and the freestream [21].

$$\boldsymbol{C_P = (p_b - p_a) \cdot \left(0.5 \cdot \rho \cdot {v_x}^2\right)^{-1}} \qquad (11)$$

3.1. Case studies

For drag coefficient calculation two method can be used with adequate precision, one is wind tunnel measurement and the other is numerical simulations. The wind tunnel measurements usually require large volume to examined the influence of the flow on the body. The construction of a model that can be placed in a wind tunnel is costly, however it is necessary to know a real life measured value. For numerical simulations it is easier to build new vehicle geometries and test is before productions. Although the precisions of these simulations should be always questionable and it should be validated.

It was shown it the work of Kim et. al. than on larger blunt shaped vehicles the drag could be significantly reduced by fairings. The tractor trailer drag coefficient was reduced by 26.5% which lead to 13.4 % fuel consumption reduction. The input data were gathered with a low speed wind tunnel combined with particle image velocimetry method. [22]

With a “rear under-body slice” shape optimization Rakibul Hassan et. al. have managed to increase the performance of a racing car. The C_D was reduced by 22%, idea was that the large low pressure zone made pressure drag and with the shape modification this pressure zone was reduced. [23]

Li et. al. [24] shown that a car with an aerodynamic drag coefficient of 0.346 can be reduced by using active grille shutter control mechanism. At high speed travel it could reduce drag of an automobile by 2.91% which could reduce the fuel consumption. The computational model was not discussed thoroughly however, it was stated that the external part of the vehicle and the internal part of the engine room.

Along the C_D the C_p becomes more relevant when the platooning is examined. For passive aerodynamic drag reduction platooning can be also utilized to save fuel. Platooning is when multiple vehicles are following the lead vehicle. This phenomenon was examined with CFD by Jacuzzi et. al. [21] when two NASCAR car turbulence was examined with numerical simulations. It was concluded the drag reduction peaks when the following vehicle is between 0.5 and 1 body length from the lead.

4. Conclusion

The goal of the paper was to highlight the crucial points that could cause losses and to show how can these estimated. Our further goals to have an UpToDate loss coefficients and calculation methods for further vehicle-energetic-modelling.

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References

[1] U.S. Department of Energy. 2000. “Technology Roadmap for the 21st Century Truck Program, a government---industry research partnership.” Technical Report 21CT---001, December.

[2] Thomas Curry, Isaac Liberman, Lily Hoffman-Andrews & Dana Lowell. Reducing Aerodynamic Drag & Rolling Resistance from Heavy-Duty Truks . 1000 Elm Street, 2nd Floor Manchester, NH 03101 : M.J. Bradley & Associates LLC, 2012.

[3] Beata Świeczko-Żurek, Piotr Jaskula, Jerzy A. Ejsmont, Agnieszka Kędzierska, Paweł Czajkowski: Rolling Resistance And Tire/Road Noise On Rubberized Asphalt Pavement In Poland. Proceedings of the Rubberized Asphalt-Asphalt Rubber, Las Vegas, USA, October 2015

[4] Wiegand, B., "Estimation of the Rolling Resistance of Tires," SAE Technical Paper 2016-01-0445, 2016, doi:10.4271/2016-01-0445.

[5] Yudhidya WICAKSANA, Nuhindro Priagung WIDODO, Suseno KRAMADIBRATA, Ridho Kresna WATTIMENA, Johanes Wesley SIGALINGGING, Muhammad RIZKY1 and NARDONO: Determining Rolling Resistance Coefficient on Hauling Road Using Dump-truck in Open Pit Coal Mine. International Symposium on Earth Science and Technology 2011

[6] Clark, S.K., et al., "Rolling Resistance of Pneumatic Tires," The, University of Michigan, Interim Report No.UM-010654-3-1, July 1974

[7] Thomas D. Gillespie: Fundamentals of Vehicle Dynamics, Society of Automotive Engineers, 1992.

[8] Duda, M.: Der geometrische Verlustbeiwert und die Verlustunsymmetrie bei geradverzahnten Stirnradgetrieben, Forschung im Ingenieurwesen 37 VDI-Verlag, 1971

[9] Niemann, G., Winter, H.: MaschinenelemepartI. Springer, Berlin, 1989

[10] Dirk Strasser: Einfluss des Zahnflanken- und Zahnkopfspieles auf die Leerlaufverlustleistung von Zahnradgetrieben, Dissertation zur Erlangung des Grades Doktor-Ingenieur, Fakultät für Maschinenbau, Ruhr-Universität Bochum, 2005

[11] Polák József, Vida Bálint: Hajtómű részterhelésének veszteségvizsgálata és annak jelentősége. Budapest : IFFK 2013 Budapest, 2013. ISBN 978-963-88875-3-5.

[12] Mihály Kozma: Friction loss of gears, Machine, October-November 2004

[13] Stribeck, R.: Kugellager für beliebige Belastungen, VDI Zeitschrift, Band 45, Heft 3, seite. 73 – 79, 1901

[14] Palmgren, A.: Neue Untersuchungen über Energieverluste in Wälzlagern, VDI Berichte, Band 20, seite 117 – 121, 1957

[15] Koryciak, J.: Einfluss der Ölmenge auf das Reibmoment von Wälzlagern mit Linienberühnung, Dissertation, Ruhr-Universität Bochum, 2007

[16] The SKF model for calculating the frictional moment. www.skf.com Download Date:2020. 01.28.

[17] Anderson, N.E., Loewenthal, S. H., "Design of Spur Gears for Improved Efficiency," ASME, JMD, Vol. 104, pp. 767-774, 1982.

[18] R. Martins, J. Seabra, Ch. Seyfert, R. Luther, A. Igartua and A. Brito: Power Loss in FZG gears lubricated with industrial gear oils: Biodegradable Ester vs. Mineral oil, Tribology and Interface Engineering Series, Volume 48, 2005, Pages 421-430

DOI: 10.21791/IJEMS.2020.2.27.

[19] R. Pradhan, S. K. Majhi, J. K. Pradhan, and B. B. Pati, "Antlion optimizer tuned PID controller based on Bode ideal transfer function for automobile cruise control system," *J. Ind. Inf. Integr.*, vol. 9, no. January, pp. 45–52, 2018, doi: 10.1016/j.jii.2018.01.002.

[20] S. Gudmundsson, *General Aviation Aircraft Design: Applied Methods and Procedures*. Elsevier Inc., 2013.

[21] E. Jacuzzi and K. Granlund, "Passive flow control for drag reduction in vehicle platoons," *J. Wind Eng. Ind. Aerodyn.*, vol. 189, no. March, pp. 104–117, 2019, doi: 10.1016/j.jweia.2019.03.001.

[22] J. J. Kim, J. Kim, T. Hann, D. Kim, H. S. Roh, and S. J. Lee, "Considerable drag reduction and fuel saving of a tractor–trailer using additive aerodynamic devices," *J. Wind Eng. Ind. Aerodyn.*, vol. 191, no. March, pp. 54–62, 2019, doi: 10.1016/j.jweia.2019.05.017.

[23] S. M. Rakibul Hassan, T. Islam, M. Ali, and M. Q. Islam, "Numerical study on aerodynamic drag reduction of racing cars," *Procedia Eng.*, vol. 90, pp. 308–313, 2014, doi: 10.1016/j.proeng.2014.11.854.

[24] J. Li, Y. Deng, Y. Wang, C. Su, and X. Liu, "CFD-Based research on control strategy of the opening of Active Grille Shutter on automobile," *Case Stud. Therm. Eng.*, vol. 12, no. May, pp. 390–395, 2018, doi: 10.1016/j.csite.2018.05.009.