SZENT ISTVÁN UNIVERSITY

Analysis of the motion of vehicles running onto terrain

Thesis of PhD work

László Máthé

Gödöllő, Hungary
2014

Doctoral school Denomination:	Mechanical Engineering Doctoral School
Science:	Agricultural Engineering
Leader:	Prof. Dr. István Farkas Professor, DSc Faculty of Mechanical Engineering Szent István University, Gödöllő, Hungary
Supervisor:	Prof. Dr. Lajos Laib Professor emeritus, CSc Institute of Process Engineering Faculty of Mechanical Engineering Szent István University, Gödöllő, Hungary
Co-supervisor:	Prof. Dr. Peter Kiss Professor, PhD Institute of Process Engineering Faculty of Mechanical Engineering Szent István University, Gödöllő, Hungary

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Affirmation of head of school	Affirmation of supervisors

CONTENTS

1. INTRODUCTION, OBJECTIVES

The research is being conducted as part of the NTP Crash project, which is supported by the Hungarian National Innovation Office.

Vehicle accidents on terrain cause many problems for forensic investigators. Experts have stated that computer simulation analysis of accidents occurring on terrain can only give approximate results. It is necessary to measure the soil's mechanical parameters to make a good assessment of terrain accidents.

The main aim of the research presented here is to determine the initial speed of a vehicle entering terrain at the moment it runs off the road. Series of field measurements were carried out with the primary aim of recording data for set up a later soil database to be used in the simulation of motion of vehicles involved in run-off accidents. The measurements were used to determine travel resistances which acting against the rolling of the wheel, a required parameter for the determination of speed.

A vehicle leaving a surfaced road enters the adjacent terrain with a certain kinetic energy. Its motion is affected by larger terrain obstacles and by vibrational acceleration induced by micro-obstacles. The deceleration and halting of the vehicle is influenced by travel resistances arising from the vehicle-soil interaction. The run-off speed (initial speed) of a vehicle which comes to a halt on the terrain may be calculated indirectly knowing the travel resistances and the distance traveled on the terrain.

Knowledge of the vehicle's speed is crucial in accident investigations. Investigators attempt to determine the speed of the vehicle in each case from tracks left on the surfaced road or the terrain. The biggest problem arises with the terrain, whose effects can only be approximated by empirical quantities

Determination of the speed requires knowledge of the coefficient of rolling resistance on the specific soil. After an accident, the only information available comes from the tracks, the cone index measurement, and the soil type, and vehicle's parameters. The further aim is to create a model that uses the soil deformation, load-bearing capacity of soil, and the contact surface of tire.

2. MATERIAL AND METHOD

To implement the research objectives and validate the model, pulling tests were carried out on level ground. The main purpose of the field measurements was to determine the wheel sinkage, rolling resistance factor and the bulldozing factor on soils of various load-bearing capacity (cone index). Measurements of deceleration distance were also carried out by on a moving vehicle left to roll in neutral.

At the moment the vehicle leaves the surfaced road, it has kinetic energy. Its further motion is determined by the physical and mechanical laws of the vehicle-terrain interaction. The various motion resistances acting on the vehicle cause it to stop after a certain distance, the distance that its speed and kinetic energy diminish to zero.

2.1. Measurement methods

One of the main parameters measured was the pulling force, which was the towing force applied to the towed vehicle. This was measured by a 50 kN load cell fitted to the drawbar.The distance traveled in the tests was measured by a shaft encoder which measured the revolution of a fifth wheel. The various experimental settings are designated by a letter and a number (for example cultivator-tilled, 1.5 bar: K1.5), where the letter corresponds to the soil and the number to the tire inflation pressure on the test vehicle. The test soil conditions and their designations: B = Concrete; T = Stubble; H = Harrowed (disc harrow); K = Cultivator-tilled. The tire inflation pressures on the front and rear axles were: p_{tire1} = 1.5 bar; p_{tire2} = 1.8 bar; p_{tire3} = 2.1 bar; p_{tire4} = 2.4 bar. The four-wheel drive test vehicle was fitted with Taurus 6.50-16 tires (Taurus Agricultural Tyres Ltd, Hungary). The tires were inflated to pressures between their lower and upper pressure limits. Speed of travel of towed vehicle: v = 10 km/h. The vehicles used for the measurements were a John Deere 6600 tractor, the pulling vehicle, and GAZ-69 four-wheel drive vehicle, which was pulled.

2.1.1. Measurement on concrete surface

Towing on concrete corresponds to the deformable tire-rigid track interaction. Comparison of the measurement on concrete with those on agricultural land yields the tire deformation loss. Here, the vehicle was not towed using the drawbar designed for terrain, because there is no significance in having a virgin (undeformed) surface. The towed vehicle was coupled behind the tractor, and the pulling force was measured (Fig. 2.1.).

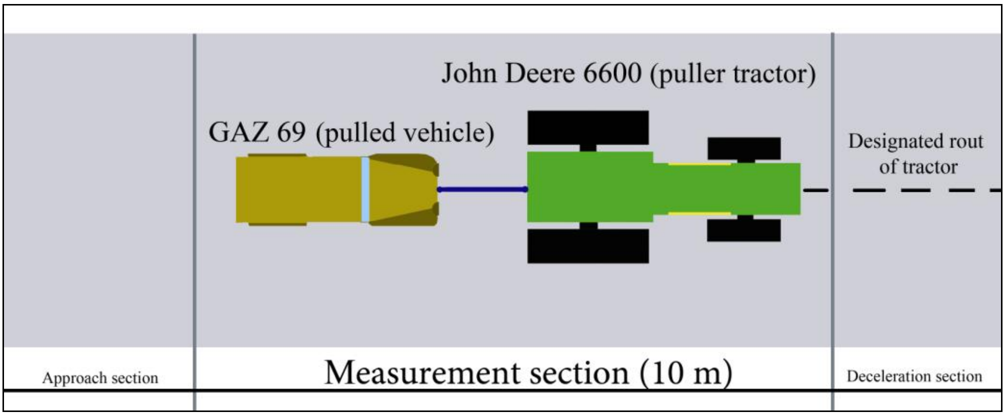

Figure 2.1. Pulling test on concrete.

2.1.2. Measurement on arable land

The test field had an area of 300x100 m. The tests were carried out on the same field on soil in three different conditions: wheat stubble, harrow-tilled wheat stubble and subsequent tilling by cultivator. The measurements were carried out on 60 m test strips (Figure 2.2.), comprising a 10 m measurement section and 25 m approach and deceleration sections. For each soil condition, measurements were made with four different tire inflation pressures, so that there were four measurement sections on each area – stubble, harrowed and cultivated. To enable determination of the vertical soil deformation, every measurement had to be carried out on an undeformed area of ground.

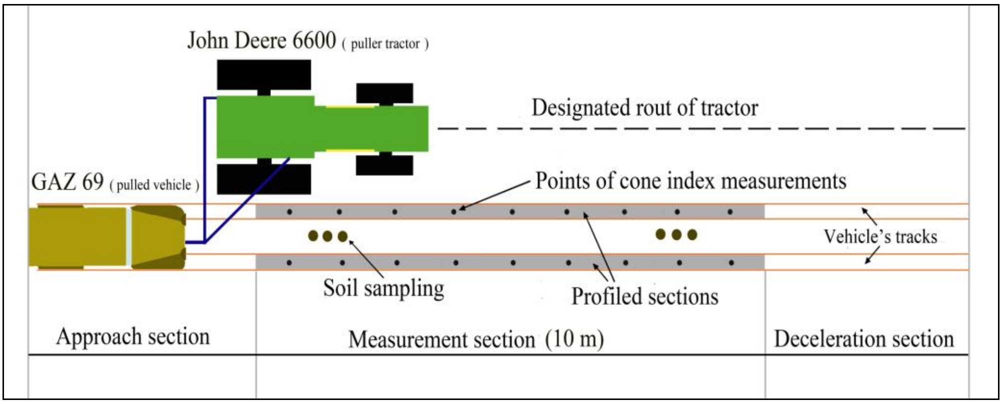

Figure 2.2. Pulling test on arable land.

The special drawbar used for towing on arable land enabled the test vehicle to travel over an undisturbed surface. The main measurements in the arable-land tests were of rolling resistance, pulling force, and soil deformation.

2.1.3. Bulldozing effect

Field measurements were also carried out to measure the bulldozing effect and thus obtain the coefficient of bulldozing resistance for the model. The measurements were performed using a towed vehicle. The vehicle was accelerated to three different speeds, and then the vehicle brake was applied to cause bulldozing at the wheel. The speeds were 10, 15 and 20 km/h, and each test was performed on a previously undisturbed surface of stubble, harrowed and cultivated land. After the tire sank into the soil and caused bulldozing, the depth of sinking and the height of soil building up in front of the wheel were measured. The pulling force was also measured in the tests.

2.1.4. Measurement with driven vehicle

The purpose of the measurement was to test the deceleration of the vehicle in varying terrain conditions (soil conditions). The measurements were carried out on concrete, a grassy surface, stubble, and harrowed and cultivated soil. The measurements were performed with a driven vehicle at tire inflation pressure of 2.1 bar and speeds of 10, 20 and 30 km/h. After the vehicle reached the desired speed and reached a designated measurement point, the driver put the vehicle into neutral and allowed it to freewheel. When it stopped, the distance between the measurement point and the stopping point was measured. This gave information on how the travel resistances slowed down and stopped the vehicle on soil of different cone index, and how far the vehicle traveled before it stopped.

2.1.5. Measurement of soil profile

The magnitude of the vertical soil deformation was determined by a terrain profilometer using the principle of communicating vessels. Each measurement section was profiled in the virgin and deformed condition. Profiles were taken in 10 cm steps. The profile was measured in front of, and behind, the GAZ-69, relative to the same base surface, the difference giving the magnitude of the vertical soil deformation.

2.1.6. Determination of tire contact surface

During the measurements, the tire pressure was a varied parameter. As a result, the contact surface of the tire changed. The contact surface was determined after each tire pressure changes and on all soil conditions and on concrete as well. On concrete the tire left footprint on indigo paper, on ground a special powder was sprinkled around the tire. In both cases, the left behind footprints were interpreted as an ellipse. The area of the ellipse was calculated by the diagonals.

2.2. Model for speed analysis

In the substantive part I deal with three key areas that form the basis of all possible outcomes. These cases are the following:

- The vehicle in neutral runs out into the field, and then stops.
- The vehicle uses engine brake when it runs out into the field, and then stops.
- The vehicle with braked wheels and engine brake runs out into the field, and then stops.

At the moment the vehicle leaves the surfaced road, it has kinetic energy. Its further motion is determined by the physical and mechanical laws of the vehicle-terrain interaction. The various motion resistances acting on the vehicle cause it to stop after a certain distance, the distance that its speed and kinetic energy diminish to zero. In addition to these resistances, the motion of the vehicle is determined by vibration acceleration induced by terrain unevenness, and by the number and size of macro-obstacles it encounters:

$$\frac{m\cdot\Delta v^2}{2}=\sum_{i=0}^{n-1}\left(\int_{s_i}^{s_{i+1}}F_{t_i}\cdot ds+E_{i\,\mathrm{vibrations}}+E_{i\,\mathrm{macro-obstacles}}+E_{i\,\mathrm{spn}}\right), \qquad (2.1.)$$

where:

m	vehicle mass [kg]
Δv	change of speed of vehicle after leaving the road [m/s]
s	deceleration distance [m]
F_t	tractive force against the vehicle’s motion [N]
$E_{i\ \mathrm{vibration}}$	energy lost to vibration acceleration [J]
$E_{i\ \mathrm{macro-obstacles}}$	energy lost to macro-obstacles [J]
$E_{i\ \mathrm{spin}}$	energy lost to vehicle spin [J]

The following equation describes the motion of the vehicle in the direction of travel and expresses that the tractive force is equal to the total of travel resistances:

$$F_t=F_{rr}+F_{air}+F_s+F_b+F_i \quad [\mathrm{N}], \qquad (2.2.)$$

where:

F_t	tractive force [N]
F_{rr}	rolling resistance (bulldozing resistance in case of bulldozing) [N]
F_{air}	air resistance [N]

- F_s	slope resistance [N]
- F_b	brake force (engine brake + powertrain loss) [N]
- F_i	force requirement for deceleration or acceleration [N]

If the vehicle spins approximately at a radius of the wheelbase, then the total spin energy is:

$$E_{i\,spin} = 2L_t \cdot \pi \frac{m \cdot g}{2} \cdot f \quad [J], \tag{2.3.}$$

where:

- L_t	wheelbase [m]
- f_s	tire side slip factor [-]

Simplifying equation (2.1.), and taking into account only the motion resistances, (2.4.) gives the following relation:

$$\frac{m \cdot \Delta v^2}{2} = \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} (F_{rr_i} + F_{s_i} + F_{air_i} + F_{b_i} + F_{i_i}) \cdot ds \right). \tag{2.4.}$$

If the vehicle stops on the terrain, i.e. its speed becomes zero, then *Δv* is equal to the run-off speed ($v_{run\text{-}off}$).

$$v_{run-off} = \sqrt{\frac{2 \cdot \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} (F_{rr_i} + F_{s_i} + F_{air_i} + F_{b_i} + F_{i_i}) \cdot ds \right)}{m}} \quad [m/s]. \tag{2.5.}$$

3. RESULTS

In accordance with the objectives set out in the introduction I completed my measurements. In the previous chapter I presented the preparation of experiments, the used equipments, instruments and measurement methods. In this chapter, the measured, reported, and new scientific results are presented.

3.1. Determination of coefficient of rolling resistances

The rolling resistance factor for each soil type and tire inflation pressure was calculated from the test figures using the equation (3.1.):

$$f_{rr} = \frac{F_t \mp m \cdot g \cdot \sin\alpha - \frac{1}{2} \cdot A \cdot c_w \cdot \rho_{air} \cdot v^2}{m \cdot g \cdot \cos\alpha} \text{ [-].} \qquad (3.1.)$$

The relation (3.1.) is not suitable for the speed determination, because after an accident the tractive force is not known.

To determine the speed of a run-off-road vehicle, the coefficient of rolling resistance must be known, and appropriate to be described by easily determinable parameters. I found in the literature a relation that uses terrain and vehicle parameters for the determination of rolling resistance. Equation (3.2.) gives the calculation of rolling resistant in case of on wheel, and equation (3.3.) gives the calculation of coefficient of rolling resistance:

$$F'_{rr} = \frac{B \cdot p_{ground} \cdot z}{n+1} \text{ [N],} \qquad (3.2.)$$

$$f'_{rr} = \frac{F_r}{Q} = \frac{B \cdot p_{ground} \cdot z}{(n+1) \cdot Q} = \frac{B \cdot z}{(n+1) \cdot A_{tire}} \text{ [-],} \qquad (3.3.)$$

where:

f_{rr}’	coefficient of rolling resistance in case of one wheel [-]
F_{rr}’	rolling resistance in case of one wheel [N]
Q	wheel load [N]
z	soil deformation (wheel sinkage) [m]
B	tire width [m]
p_{ground}	ground pressure [Pa]
A_{tire}	tire contact surface [m^2]
n	factor of load bearing capacity of soil [-]

Based on my measurements I could determine the contact surfaces of diagonal and radial type tires. In case of diagonla type tires, at nominal wheel load, the following (3.4.) relation is useable:

$$A_{tire(D)} = \frac{Q}{10 \cdot p_{tire} \cdot \left[1{,}2 - 1{,}2 \cdot \left(\frac{z}{D}\right)^{0{,}44}\right]} \quad [cm^2]. \tag{3.4.}$$

In case of radial type tires, at nominal wheel load, the following (3.7.) relation is useable:

$$A_{tire(R)} = \frac{Q}{10 \cdot p_{tire} \cdot \left[0{,}75 - 0{,}75 \cdot \left(\frac{z}{D}\right)^{0{,}44}\right]} \quad [cm^2]. \tag{3.5.}$$

Where Q is wheel load [N], p_{tire} is tire inflation pressure [bar], z/D is relative wheel sinkage [-].

Using the relations (3.4.) and (3.5.) I created nomograms (Fig. 3.1. and 3.2.) in order to give help to the experts to determine from the relative wheel sinkage, wheel load, and tire inflation pressure easily and quickly the tire contact surface which is an important input parameter in the run-off speed calculation.

On Fig. 3.1. and 3.2., the same colours of curves show the same tire pressures but the saturation separates them, so the effect of different wheel loads can be seen in the shape of curves. Four tire inflation pressure values (1,5-1,8-2,1-2,4 bar) and four wheel load values were taken into account during the nomogram creation: Q_1 = 2500 N, Q_2 = 4500 N, Q_3 = 6500 N, Q_4 = 8500 N.

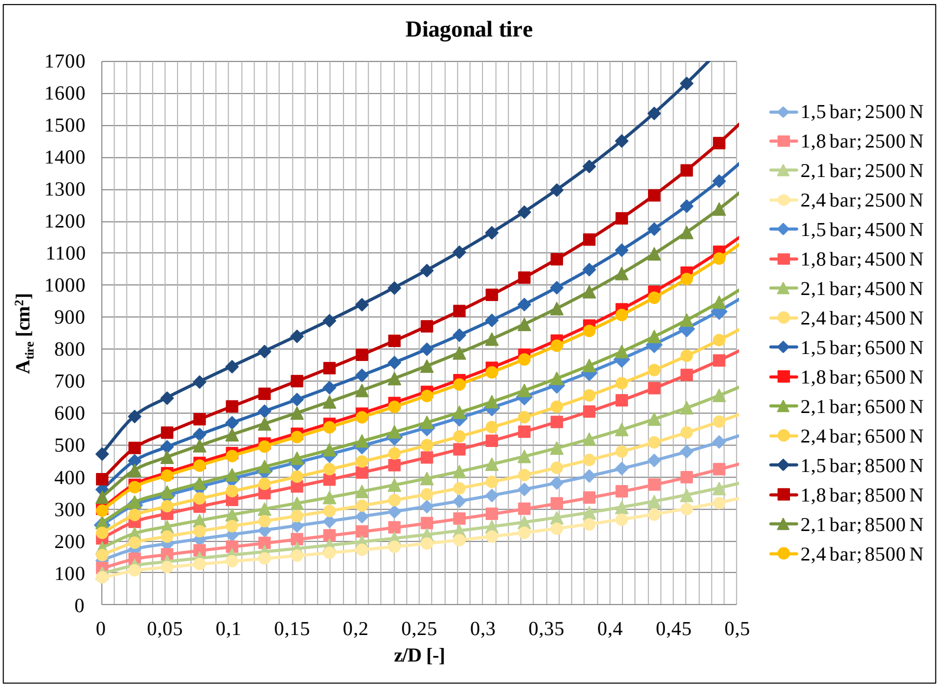

Figure 3.1. Tire contact area as a function of relative wheel sinkage, in case of diagonal tires.

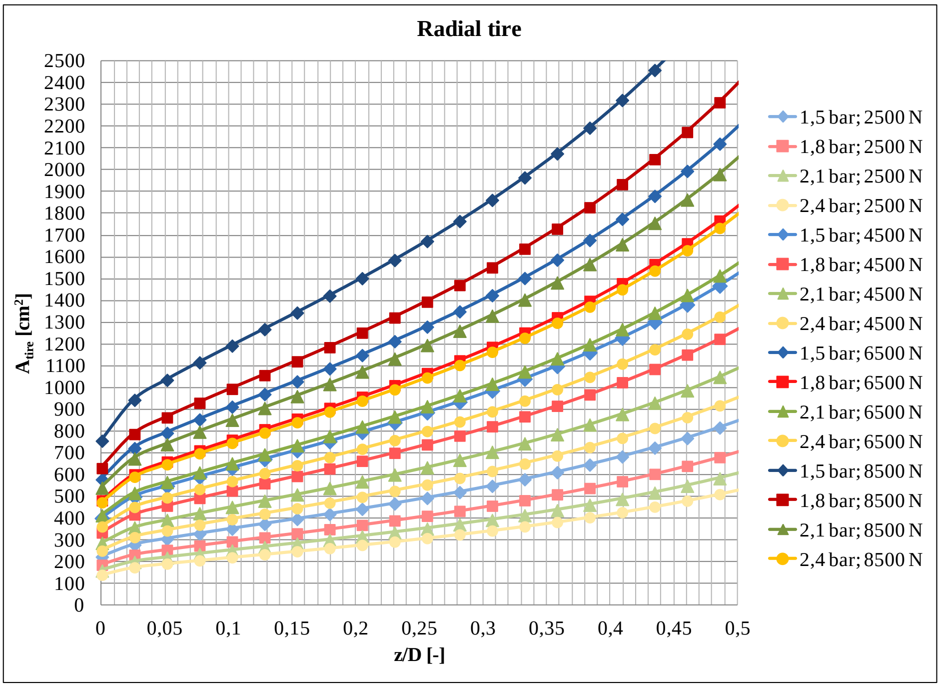

Figure 3.2. Tire contact area as a function of relative wheel sinkage, in case of radial tires.

The equation (3.3) valid for single wheel, it cannot be used to the calculation of speed. It is necessary to examine the relation between the rolling resistance coefficients measured during the multipass, and rolling resistance coefficients in case of single wheel. I used the formula (3.3) to determine for each series of measurements the f_{rr} 'values.

In order to investigate the resistance caused by the terrain, I subtracted the tire deformation resistance which was determined by the measurement in concrete, from both coefficients of rolling resistance. This value ($f_{rr(def)} = 0.03$) is added later to the function that describes the relationship.

The function of the coefficient of rolling resistances determined for four wheel and one wheel, is given on Figure 3.3. It can be seen that the correlation is R^2=0.99.

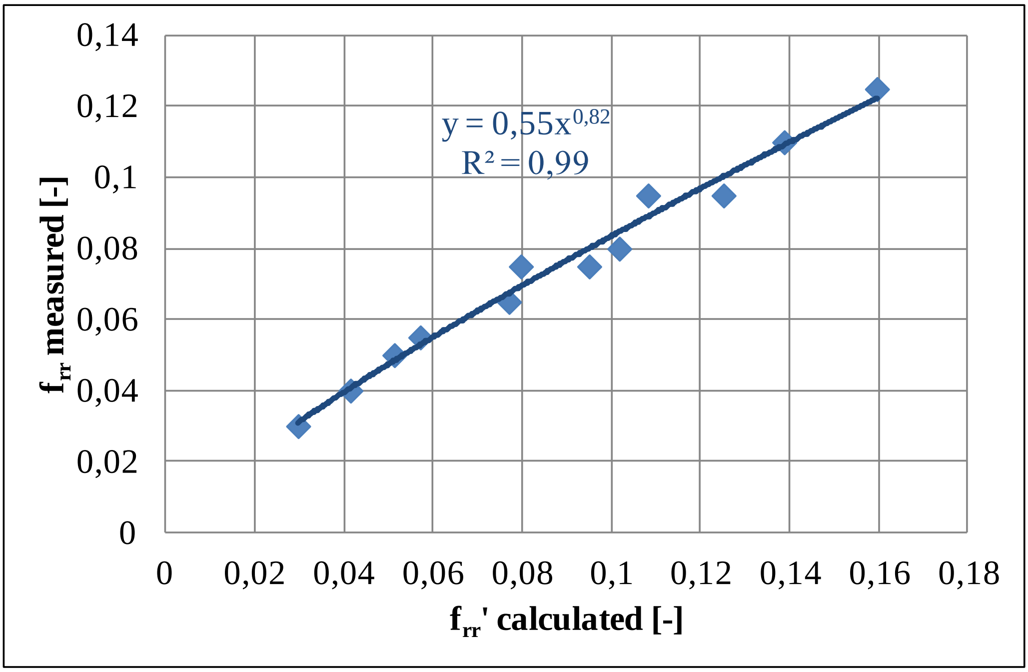

Figure 3.3. The rolling resistance coefficients determined by the field measurement data, as a function of calculated rolling resistance coefficient, valid for one-wheel, without tire deformation.

Using the power function of curve the rolling resistance coefficient for the case of four-wheel and multipass can be determined:

$$f_{rr} = 0{,}03 + 0{,}55 \cdot \left(\frac{B \cdot z}{(n+1) \cdot A_{tire}} \right)^{0{,}8} \quad [-]. \qquad (3.6.)$$

Using the formula (3.6), rolling resistance coefficients were determined, which were plotted as a function of rolling resistance coefficients identified from the field measurements. In the calculation the tire caused permanent deformation resistance values were taken into account. Using the equation (3.6), the coefficients obtained from measurements and the modeled coefficients have a correlation of $R^2 = 0.98$, so the formula can be used well.

3.2. Examination of bulldozing effect

If the vehicle brakes in loose soil in which the vegetation is negligible, a high risk of bulldozing-effect appears. As a result, the kinetic energy of the vehicle is greatly reduced, thus resulting in high deceleration.

In case of bulldozing, the coefficient of bulldozing resistance (f_{bull}) must be taken into account, which has the same interpretation as the rolling resistance coefficient (f_{rr}).

In case of bulldozing, the tractive force is the following:

$$F_t = F_{bull} + F_s \text{ [N]}, \qquad (3.7.)$$

where:

F_t	tractive force [N]
F_{bull}	bulldozing resistance [N]
F_s	slope resistance [N]

The traction for is given by (3.8.):

$$F_t = f_{bull} \cdot m \cdot g \cdot \cos\alpha \pm m \cdot g \cdot \sin\alpha \text{ [N]}. \qquad (3.8.)$$

If the traction force is known, the bulldozing coefficient is given by (3.11.):

$$f_{bull} = \frac{F_t \mp m \cdot g \cdot \sin\alpha}{m \cdot g \cdot \cos\alpha} \text{ [-]}. \qquad (3.9.)$$

Using the measurement results and the equation (3.9.) I determined the coefficients of bulldozing resistance (f_{bull}), and using the equation (3.10.) rolling resistance coefficients were calculated.

$$f_{rr} = 0{,}03 + 0{,}55 \cdot \left(\frac{B \cdot H}{(n+1) \cdot A_{tire}} \right)^{0{,}8} \text{ [-]}. \qquad (3.10.)$$

The calculation of the rolling resistance coefficient is based on the relationship (3.6.), but I put “H” in the place of "z" wheel sinkage. If there is no bulldozing, that no amount of ground rolled, the value of "H" is equal to the value of "z". It is possible that the vehicle brakes intermittently so it can pass through the rolled soil. In this case, the sinkage rate and the rolled soil height near the wheel are known. In the view of this, the bulldozing resistance coefficient could be calculated with a good approximation.

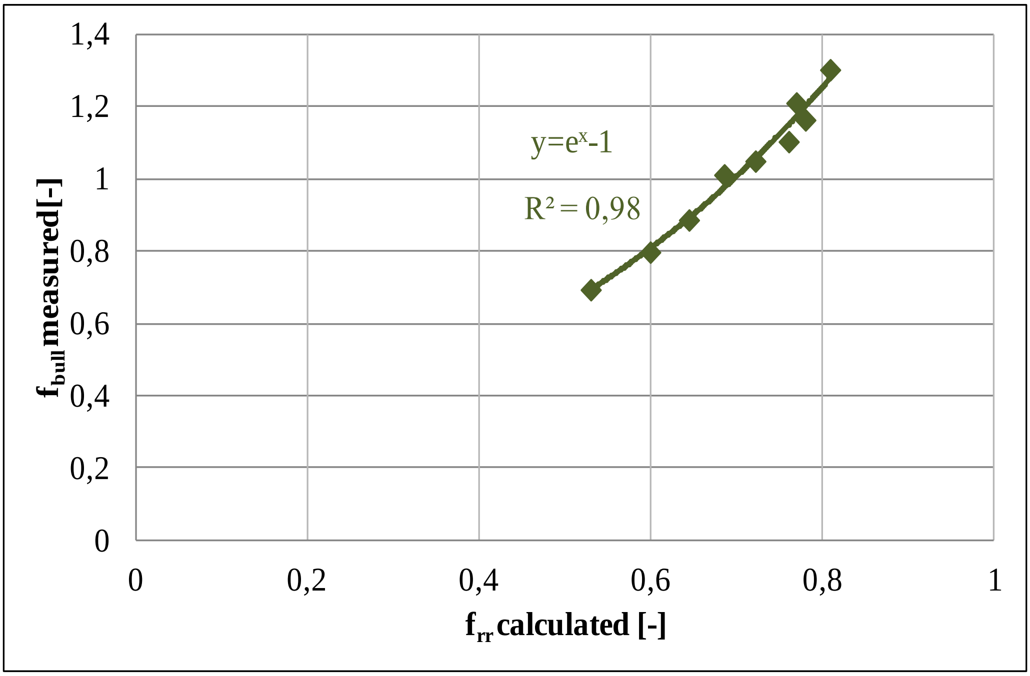

Figure 3.4. The coefficients of bulldozing resistance, determined by field measurement data, as a function of calculated rolling resistance coefficients.

The figure shows that the fitted exponential function curve gives correlation of R^2 = 0.98, which is very favorable. I wrote the definition of bulldozing resistance coefficient (f_{bull}) using a rolling resistance coefficient of the equation (3.10.).

$$f_{bull} = \exp(f_{rr}) - 1 = \exp\left[0{,}03 + 0{,}55 \cdot \left(\frac{B \cdot H}{(n+1) \cdot A_{tire}}\right)^{0{,}8}\right] - 1\,[-]. \quad (3.11.)$$

The correlation between the coefficients of rolling resistance, determined from field data, and the calculated coefficients, using the equation (3.11.) is sufficiently high, R^2=0,98.

If the run-off-road vehicle doesn’t roll on its wheels clearly but induces bulldozing, the coefficient of bulldozing resistance is important to be known for the speed determination.

It is important that the forensic experts can determine the bulldozing resistance coefficient using basic ground and vehicle data. Using the equation (3.11) gives a good approximation to determine the factor.

3.3. Examination of run-off-road vehicle speed

I assume that after the road-leaving accident the vehicle enters the terrain. According to my suggestion the aim of the calculation is to determine the Δv of the vehicle which has kinetic energy. The run-off speed is equal to Δv.

The input, output data of the model and the used relations are shown in the following subsection.

3.3.1. Input parameters of the model

Input data related to vehicle:

m	vehicle mass [kg]
B	tire width [m]
D	tire diameter [m]
Q	one wheel load [N]
A_{tire}	tire contact surface [m^2]
p_{tire}	tire pressure [Pa]
L_t	wheelbase [m]
f_{eb}	coefficient of engine brake [-]
f_{pl}	coefficient of powertrain loss [-]

Input data related to terrain:

$CI_{z0=0}$	cone index at a depth of $z_0=0$ [MPa]
$CI_{z0=L}$	cone index at a depth of $z_0=L$ [MPa]
n	factor of load-bearing capacity of soil [-]
α	slope angle [°]
z	soil deformation, wheel sinkage [m]
h	height of rolled soil, calculated from the ground level [m]
H	sum of z and h [m]
s	deceleration distance [m]
f_{rr}	coefficient of rolling resistance [-]
f_s	tire side slip factor [-]
f_{bull}	coefficient of bulldozing resistance[-]

3.3.2. Output parameters of the model

In case of rolling motion, continuous or discontinuous tracks left by the vehicle, the run-off speed is calculated by the following relation:

$$v_{run-off} = \sqrt{\frac{2 \cdot \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} (F_{rr_i} + F_{s_i} + F_{eb_i} + F_{pl_i}) \cdot ds + E_{i\,spin} \right)}{m}} \text{ [m/s].} \qquad (3.12.)$$

In equation (3.12.) the spin of vehicle around vertical axis is taken into account. Simplifying the calculation of speed:

$$v_{run-off} = \sqrt{2 \cdot \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} [g \cdot (\cos\alpha \cdot f_{rr} \pm \sin\alpha + f_{eb} + f_{pl})] \cdot ds + L_t \cdot \pi \cdot g \cdot f_s \right)} \text{ [m/s].} \quad (3.13.)$$

In case of bulldozing effect, the coefficient of rolling resistance must be replaced in equation (3.12.) by coefficient of bulldozing resistance. During deceleration there is weight transfer on the front axis which increases the possibility of bulldozing. In this situation the spin around vertical axe is not relevant.

$$v_{run\text{-}off} = \sqrt{\frac{2 \cdot \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} (F_{bull_i} + F_{s_i} + F_{eb_i} + F_{pl_i}) \cdot ds \right)}{m}} \text{ [m/s].} \qquad (3.14.)$$

Simplifying the equation (3.14.), the speed is given by the following relation:

$$v_{run\text{-}off} = \sqrt{2 \cdot \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} [g \cdot (\cos\alpha \cdot f_{bull} \pm \sin\alpha + f_{eb} + f_{pl})] \cdot ds \right)} \text{ [m/s].} \quad (3.15.)$$

3.4. Validation of the model by field tests

Table 3.1. describes the run-out distances at the case when the vehicle was accelerated then in neutral stopped.

During the verification, the run-out distances were input data to check the accuracy of the model. I examined that if I give the run-out distances, shown in Table 3.1., as input data to the model, how much are the speed values at the output side. The model verification was performed by Excel software, using the input data given in chapter 3.3.1. to calculate the required speed values. Adjusted speed values during the measurement and calculated speed values using the model were compared, the differences were determined.

Table 3.1. Verification of the exactness of the model.

Verification of exactness					
Measured data				**Calculated data**	**Difference**
v [km/h]	**s [m]**	**z [m]**	**n [-]**	**v [km/h]**	**Δ [%]**
10	8,5	0,005	0,6	12,74	21,51
20	27			23,39	14,49
30	64,5			34,49	13,02
10	3,5	0,021	0,7	11,42	12,43
20	12			21,14	5,39
30	28,5			32,58	7,92
10	3	0,046	1,5	12,84	22,12
20	10			23,44	14,68
25	11			24,58	1,71
30	18			31,45	4,61
35	25			37,06	5,56
10	2	0,071	1,8	11,05	9,50
20	7,5			21,39	6,50
30	15,5			30,75	2,44
35	22,5			37,05	5,53

To help the experts I prepared a nomogram using the model for speed calculation. The nomogram is shown on Figure 3.5.

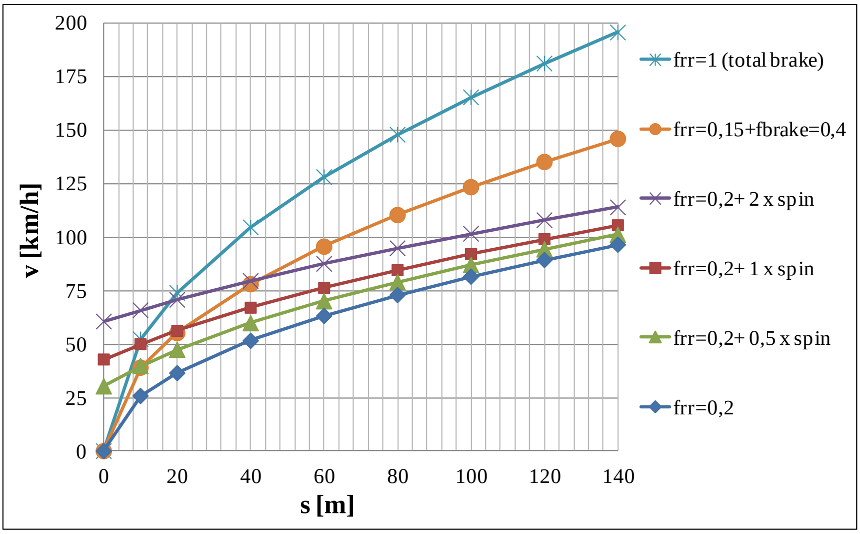

Figure 3.5. Vehicle speed as a function of stopping distance, using the relation (3.13) and (3.15.) for the creation of this nomograms.

4. NEW SCIENTIFIC RESULTS

1. I created a new calculation for determination of tire contact area. The relation takes into account the tire diameter (D), one wheel load (Q), tire inflation pressure (p_{tire}), and the relative wheel sinkage (z/D). In case of diagonal tires, the calculation is the following:

   $$A_{tire(D)} = \frac{Q}{10 \cdot p_{tire} \cdot \left[1{,}2 - 1{,}2 \cdot \left(\frac{z}{D}\right)^{0{,}44}\right]} \quad [\mathrm{cm}^2].$$

   In case of radial tire:

   $$A_{tire(R)} = \frac{Q}{10 \cdot p_{tire} \cdot \left[0{,}75 - 0{,}75 \cdot \left(\frac{z}{D}\right)^{0{,}44}\right]} \quad [\mathrm{cm}^2].$$

2. I created a new calculation for determination of coefficient of rolling resistance in case of multipass and four wheels. With the knowledge of tire width (B), tire contact area (A_{tire}), soil deformation (z) and the factor of the load bearing capacity (n), the coefficient is given by:

   $$f_{rr} = 0{,}03 + 0{,}55 \cdot \left(\frac{B \cdot z}{(n+1) \cdot A_{tire}}\right)^{0{,}8} \quad [\text{-}].$$

   This is a general relation, because it contains all of required parameters related both vehicle and terrain, which is important for the determination of rolling resistance coefficient.

3. I defined a new relation in order to determine the coefficient of bulldozing resistance. The calculation uses the coefficient of rolling resistance as input parameter. With the knowledge of tire width (B), tire contact area (A_{tire}), the sum of wheel sinkage and the height of the rolled soil (H) and the factor of the load bearing capacity of soil (n), the coefficient of bulldozing resistance is given by the following equation:

   $$f_{bull} = \exp(f_{rr}) - 1 = \exp\left[0{,}03 + 0{,}55 \cdot \left(\frac{B \cdot H}{(n+1) \cdot A_{tire}}\right)^{0{,}8}\right] - 1 \, [\text{-}].$$

4. I determined the run-off speed of a vehicle after leaving the built road. The principle of the calculation is that a vehicle after the road leaving enters the terrain then stops, its speed is reduced to 0. Then by measuring the distance left by the vehicle and with the knowledge of the effect of motion resistances, the run-off speed is determinable. The method of arrival onto terrain should be examined separately.

   The following basic information is required to determine the speed: stopping distance, slope angle, the rolling resistance coefficient, engine brake loss, powertrain loss, and in case of bulldozing, the bulldozing resistance coefficient. The determination of the velocity was made in three basic cases: a vehicle enters the terrain without brake, rolling in neutral then stops; the vehicle is slowed down by engine brake and the vehicle is braked by wheels, causing bulldozing effect. I also took into account the possibility that the vehicle spins around its vertical axis. The run-off speed is determined by the following equations:

   In case of rolling:

$$v_{run-off} = \sqrt{2 \cdot \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} [g \cdot (\cos\alpha \cdot f_{rr} \pm \sin\alpha + f_{eb} + f_{pl})] \cdot ds + L_t \cdot \pi \cdot g \cdot f_s \right)} \ [\text{m/s}].$$

   In case of bulldozing:

$$v_{run\text{-}off} = \sqrt{2 \cdot \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} [g \cdot (\cos\alpha \cdot f_{bull} \pm \sin\alpha + f_{eb} + f_{pl})] \cdot ds \right)} \ [\text{m/s}].$$

5. I created a new method for determination of diagonal and radial tire surface area. With the knowledge of the relative wheel sinkage (z/D), one wheel load (Q), and tire inflation pressure (p_{tire}), the tire contact area (A_{tire}) is determinable by the nomograms (Fig. 3.1. and 3.2.) The nomograms give help to the experts to determine easily and quickly the tire contact surface which is an important input parameter in the run-off speed calculation.

   Four tire inflation pressure values (1,5-1,8-2,1-2,4 bar) and four wheel load values were taken into account during the creation of nomograms (Fig. 3.1. and 3.2.): Q_1 = 2500 N, Q_2 = 4500 N, Q_3 = 6500 N, Q_4 = 8500 N.

5. CONCLUSIONS AND SUGGESTIONS

A series of field measurements were carried out with the primary aim of recording data for a soil database to be used in the simulation of motion of vehicles involved in run-off accidents. The measurements were used to determine travel resistances, a required parameter for the determination of the speed of a vehicle entering terrain at the moment it runs off the road.

An important item of information in the analysis of such accidents is the vehicle’s speed, a knowledge of which permits the circumstances of the accident to be reconstructed. There are developed and widely-accepted methods of analysis for road accidents, but hardly any methods for terrain accidents. Experts have stated that computer simulation analysis of accidents occurring on terrain can only give approximate results. It is necessary to measure the soil mechanics parameters to make a good assessment of terrain accidents. Accident analysis must incorporate the soil-tire interaction and the effect of soil mechanics parameters on the vehicle’s mobility.

Previous vehicle-terrain interaction theory research by the Department of Automotive Engineering of Szent István University has proved very useful during the investigation, because the motion of a vehicle running on to terrain after an accident is governed by the vehicle-soil and tire-soil interactions.

If, following a run-off accident, the speed at which a vehicle left the road is not known, and all that can be measured are tracks left on the terrain, the accident should be examined from the viewpoint of travel resistances – the forces that slowed down and halted the vehicle. If these can be defined with sufficient accuracy, the vehicle speed at the moment it left the road can be determined from the change in kinetic energy.

With knowledge of the vehicle mass, the distance traveled on the terrain, and the effects of the soil parameters, then if the other forces acting on the vehicle are known, the speed of the vehicle as it left the road may be calculated (providing that it came to a halt on the terrain).

6. SUMMARY

Forensic investigators in every case attempt to determine the vehicle’s speed from tracks left on the surfaced road or on the adjacent terrain. The greatest problem is caused by the terrain, whose effect can only be approximated by empirical quantities.

The analysts cannot be expected to conduct examinations of the soil or the unevenness of the terrain in every case. The purpose of the research was to create a simulation model of a run-off accident capable of determining the initial speed at which the vehicle left the road.

A vehicle leaving a surfaced road enters the adjacent terrain with a certain kinetic energy. Its motion is affected by larger terrain obstacles and by vibrational acceleration induced by micro-obstacles. The deceleration and halting of the vehicle is influenced by travel resistances arising from the vehicle-soil interaction. The run-off speed (initial speed) of a vehicle which comes to a halt on the terrain may be calculated indirectly knowing the travel resistances and the distance traveled on the terrain.

To determine the run-off speed, terrain parameters are required: the coefficient of rolling resistance or bulldozing resistance; the tracks left on terrain: during the accident only the tracks are known; data measured on terrain: the cone index and the track depth can be measured, and soil type identified. Data for the vehicle can be determined from catalog or database, so the vehicle parameters are considered as known input parameter.

To implement the research objectives and validate the model, pulling tests were carried out on level ground. The main purpose of the field measurements was to determine the rolling resistance factor and the bulldozing factor on soils of various load-bearing capacity (cone index). Measurements of deceleration distance were also carried out on a moving vehicle left to roll in neutral to determine the motion resistances of the vehicle on terrain. The tests were carried out on the same field on soil in three different conditions: wheat stubble, harrow-tilled wheat stubble and subsequent tilling by cultivator.

The results of the measurements have been capable to formulate new scientific evidence that refers to the determination vehicle speed after run-off-road accidents. The results are useful for forensic experts especially if the results are integrated into software.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign language:

1. Laib, L. – **Máthé, L.** – Pillinger, Gy. (2010): The effects of the off-road vehicle on the soil cohesion and internal friction. Mechanical Engineering Letters, Vol. 4., pp. 73-91. HU ISSN 2060-3797
2. **Máthé, L.** – Kiss, P. – Laib, L. – Pillinger, Gy. (2013): Computation of run-off-road vehicle velocity from terrain tracks in forensic investigations. Journal of Terramechanics, Vol. 50. Issue 1., pp. 17-27. (IF: 0,803*)
3. **Máthé, L.** – Kiss, P. – Laib, L. – Pillinger, Gy. – Magdics, G. (2013): Run-off-road vehicle speed analysis from terrain tracks. Mechanical Engineering Letters, Vol. 10., pp. 81-90. HU ISSN 2060-3797
4. **Máthé, L.** – Magdics, G. (2013): Investigation of friction coefficient between vehicle body and soil. Hungarian Agricultural Engineering. Vol. 25., pp. 51-53. HU ISSN 0864-7410
5. **Máthé, L.** – Pillinger, Gy. (2014): Examination of an overturned towed vehicle. Journal of Tekirdag Agricultural Faculty, Vol. 11. Issue 1., pp. 63-66. ISSN 1302-7050

Referred articles in Hungarian language:

6. **Máthé, L.** (2011): Terepre futó jármű menetellenállásainak elemzése különböző talajfelszínen. GÉP, LXII. évf., 6. sz., 27-35. o., ISSN 0016-8572
7. **Máthé, L.** (2011): Terepen bekövetkező baleset elemzése a talajparaméterek figyelembevételével. Járművek és Mobil Gépek online folyóirat (http://on-and-off-road-vehicles.hu), III. évf., 1. sz., 137-151. o., HU ISSN 2060-4408
8. **Máthé, L.** (2012): Terepre futó jármű menetellenállásai. Mezőgazdasági Technika, LIII. évf. Január, 2-5. o., HU ISSN 0026 1890
9. **Máthé, L.** (2012): Mezőgazdasági terület talajparamétereinek vizsgálata. Mezőgazdasági Technika, LIII. évf. November, 2-4. o., HU ISSN 0026 1890
10. **Máthé, L.** (2013): Vályogtalaj ülepedettségének és mechanika tulajdonságainak vizsgálata. Járművek és Mobil Gépek online folyóirat (http://on-and-off-road-vehicles.hu), IV. évf., 1. sz., 9-16. o., HU ISSN 2060-4408