SZENT ISTVÁN UNIVERSITY

# Stability of Propelled Trailer Equipped Agricultural Transport Systems

Theses of Ph.D. Work

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| Affirmation of program leader | Affirmation of supervisor |

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# 1. INTRODUCTION

The subject of my thesis work is the stability analysis of transport vehicle combinations consisting of agricultural tractors and driven axle trailers, and the reduction of the accidents related to them. I pay special attention to the accidents caused by the trailer protrusion. In order to achieve the stability increase, I have developed a computer model of a vehicle park, which is capable of performing dynamical simulations of transport vehicle trains.

## 1.1. Propelled axle agricultural trailers, and the related problems

Manufacturers of agricultural vehicles has discovered early that using auxiliary front wheel drive can be advantageous by exerting larger pulling force in heavy soil conditions. Using 4WD the total mass of the tractor is involved in the production of the pulling force. In this way higher rate of the motor's torque can be converted to wheel forces. Vehicle trains used in the agricultural transport are mostly equipped with non-driven trailers, so the great portion of the mass of vehicle is not involved in the pulling force production.

In my opinion instead of ballasting the heavy tractors, involving the wheels of the trailer into the force development could be more beneficial. This could secure the mobility of the transport system in heavy soil condition, and the soil damage could be reduced as well.

Involving the wheels of the trailer in the pulling force production has the following possible advantages:

- Despite of the general tendency of the power increasing in the agricultural machinery, the weight of the tractor can be reduced.
- The agricultural transport systems can be considered and optimized as a single protrusion unit.
- By means of optimized weight and driving torque distribution the soil damage, environmental pollution and operation costs can be reduced.
- By making the transport system more independent from soil conditions, the harvesting losses can also be reduced.

Despite of the potential advantages, because of the lack of safety measures, the trailer protrusion is not part of the practical life. The origin of the problems is that the trailer can generate a side force on the rear wheels of the tractor, which certain condition can bring the tractor in instable state. The trailer can the tractor roll over or jackknife.

The conclusion can be drawn, that the tractor-trailer vehicle combination only can be used when it is equipped with control system, which can avoid the trailer drive originated accidents to happen.

## 1.2. Aimed goals of the dissertation

The goals of the thesis work can be summarized in the following three points:

1. To create a computer simulation model of an agricultural transport vehicle-park consisting of different dynamical models of tractors and trailers. The aim of this model-park is to perform stability analysis of tractor – propelled axle trailer vehicle combinations.

   During the development phase, the special properties of the agricultural transport, mainly the difficulties of the mobility on terrain have to be considered. The related models have to be universal in order to be able to take the special properties of the agricultural transport vehicles into consideration, like adjustable wheel-base and additional ballasting. The models have to be flexible in means of changeable equipment. The setting of the input data and visualization of the result has also to be easily done.

2. The investigation of the accidents of the agricultural transport systems equipped with propelled axle trailers, in order to find those parameters of which observation can be used to avoid the trailer drive originated accidents. From these parameters one can be chosen, which is the most easily can be measured or determined, and can be used for stability control algorithms.

3. To develop stability control programs that can determine different instable states of the vehicle combinations, and by interaction can re-stabilize the train.

   The stability program has to be simple, and reliable. The number of miss-alarming or miss-intervening have to minimized, while the time between occurrence of the instable state and the stabilization has to be minimized.

# 2. THE MODELS USED FOR DEVELOPING THE STABILITY-PROGRAMS

In this chapter the models used for the stability analysis of the agricultural transport vehicle trains and the methods of instability-determinations are introduced. The models I have developed, in Matlab/Simulink environment are created especially for this thesis work. The models are developed in a modular system so, that they can, besides agricultural transport systems be used for simulation other types of vehicles as well.

## 2.1. The vehicle model park developed for the task

In order to model agricultural transport systems I have developed dynamic models of different tractors and trailers. From the model vehicles vehicle combinations can be created as in the reality.

### 2.1.1. The applied vehicle model

The models are created in Matlab/Simulink environment and built in modular system. This ensures different sub-models to be changed within models, and new model units (like a trailer behind a car, a plow behind an agricultural tractor, or a different tractor) can be inserted in the vehicle model, if the simulation goals require so.

Figure 1 shows the realization of an Agricultural transport system consisting of a tractor and a propelled axle trailer. Dash-dot line surrounds the tractor, dash-line the trailer, and continuous line surrounds the coupling model, which couples the two vehicles to form the vehicle train.

Within both vehicle models (tractor and trailer, right and left side of the picture accordingly) the vehicle body, wheel-force and the user interface sub-models can be found. In the vehicle body sub-model the linear and angular accelerations of the vehicle mass are calculated from the forces acting on the body. By integrating the accelerations can the speed and rotational speed be determined. After a second integration the traveled way and rotational angle can be get.

The speed and position values then feed to the wheel-force model to calculate the wheel and suspension forces, which the feed back to the vehicle body to calculate the acceleration in the next time-step. The user interface sub-model contains the driver models. The driver model includes steering and the determination of the wheel-torque (braking and driving). Both has open and closed loop control algorithms to have pre programmed driver behavior to be used for simulating different tasks.

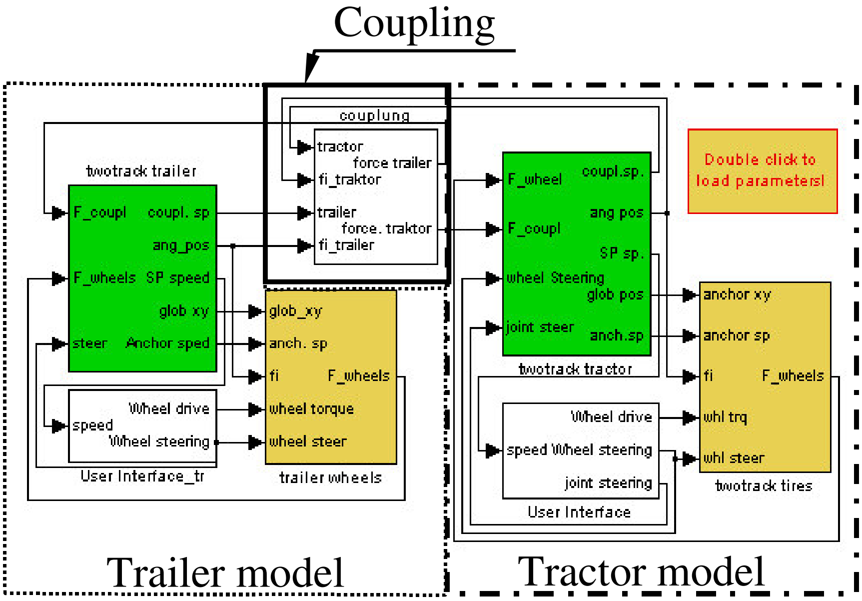



**Figure 1: The vehicle combination model in Matlab/Simulink environment**

Arrowhead lines demonstrate the flow of signal between the model blocks. The signal flows create closed loop systems. The sup-models are consisting further sub-models, which are layered in a 7-layer deep structure.

I have created an animation-window, which by simplified schemas of the vehicles helps to follow the motion of the vehicle train. It has indications for the state of the stability control system, and helps to create animations for demonstration goals.

## 2.2. Determination of the unstable state of the vehicle

The determination of the unstable state is the first level of the 2-level stability program of the vehicle, which includes the determination of the upcoming accident and warning the driver about it. The second level is an active safety system, which can interact the motion of the vehicle train to stabilize it by braking the wheels or decreasing the wheel torque.

### 2.2.1. The extended Ackermann-condition of vehicle trains

Pulling angle: The horizontal component of the angle between the pulling and the pulled vehicle. Notation: $\gamma$ ($^o$ or radians)

One method of determining the state of the vehicle is based on measuring the pulling angle, and comparing its value to the expected one. To determine the expected value of the pulling angle I have introduced the extended Ackermann conditions of vehicle trains. Figure 2 shows a tractor and a trailer attached to it. The angle of the steered wheels ($\delta_L$, $\delta_R$) is calculated by the conventional way of determining the steering angle of a 4-wheel vehicle by the method of Ackermann.

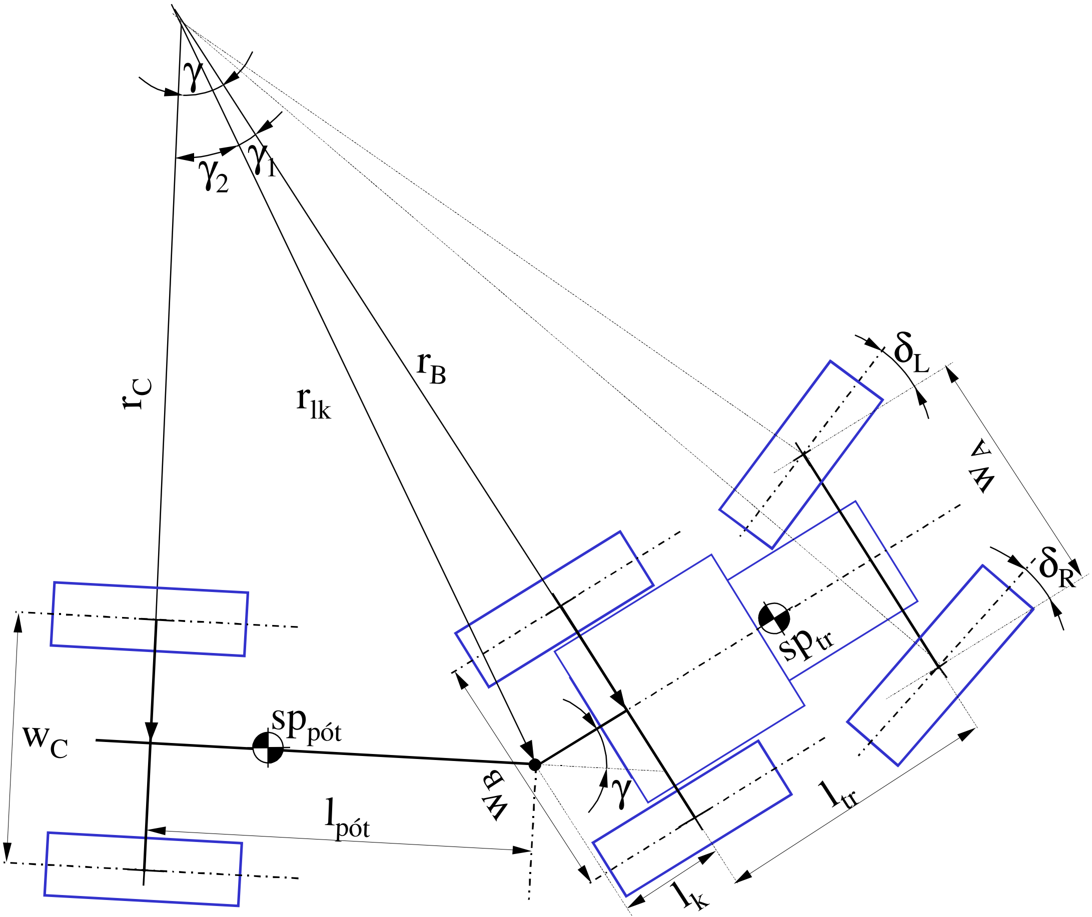



**Figure 2: The extended Ackermann-condition of vehicle trains**

The Ackermann condition of vehicle train is fulfilled when not only the axles of the wheels of the tractor, but also the wheels of the trailers are pointing in the theoretical turning center (momentan centrum). The $\gamma_{stat}$ pull-angle in the steady curving can then calculated (using the notations of Figure 2) as follows:

$$\gamma_{stat}=\gamma_1+\gamma_2 \tag{1}$$

when

$$\gamma_1 = \arctan\left(\frac{l_k}{r_B}\right) \text{ and} \tag{2}$$

$$\gamma_2 = \arcsin\left(\frac{l_{pót}}{r_{lk}}\right) = \arcsin\left(\frac{l_{pót}}{\sqrt{(l_k^2 + r_B^2)}}\right). \tag{3}$$

Equations (2) and (3) substituted in eq.(1):

$$\gamma_{stat} = \arctan\left(\frac{l_k}{r_B}\right) + \arcsin\left(\frac{l_{pót}}{\sqrt{(l_k^2 + r_B^2)}}\right) \tag{4}$$

The turning radius of the rear axle is:

$$r_B = \frac{l_{tr}}{\tan(\delta_L)} + \frac{w_A}{2} \tag{5}$$

### 2.2.2. Determination of the pulling angle

The steady state $\gamma_{stat}$ pulling angle (calculated in equation 4) is equivalent with the current value of it only in steady state curving. The reason of it is that in opposite to the $\delta_L$, $\delta_R$ steering angles of front wheel of the tractors, which immediately occur as the steering wheel is turned, the pulling angle continuously chancing as the vehicle moves. To reach its steady state value the vehicle has to travel a certain distance. My goal was to set up the model or equation which describes the actual value of the pulling angle even in continuously changing state.

The actual value of the pulling angle depends on the speed and the geometry of the vehicle, and the steering angle. With a sudden change of the steering wheel angle, a unity-step like function can be generated, which is capable of testing the behavior of the system. The response of the system to the step input signal indicates the type of it, in the means of number of energy storages. In the given case the system responded similar to the one-storage systems, so for the modeling and calculating the value of the $\gamma_{dyn}$ current pulling angle I have used a general PT1 type system.

The current value of the pulling angle can be calculated in simplified state space form as follows::

$$\begin{aligned} \dot{x} &= A \cdot (\gamma_{stat} - x) \\ \gamma_{din} &= x \end{aligned} , \tag{6}$$

here $x$ is the state variable, which in this case the $\gamma_{dyn}$ current pulling angle itself.
The $A$ coefficient of the model depend on geometry of the vehicle and its travelling speed. Its value can be calculated according to equation 7.

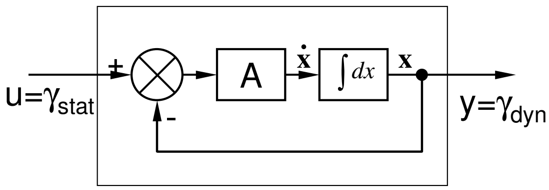



**Figure 3: Determination of $\gamma_{dyn}$ actual pull angle based on the $\gamma_{stat}$ steady-state pulling angle.**

The Figure 3 shows the block scheme realization if eq. (6) the figure uses the general nomination used in process control theories (u: input function, y: output function, x:

state variable). In this case, the matrix *A* is a scalar, and its value is the reciprocal of the time required the rear axle of the trailer to reach the position of the rear axle of the trailer.

In equation:

$$A = \frac{v_x^{tr}}{l_{pót} + l_k} \qquad \left(\frac{1}{s}\right), \tag{7}$$

where $v^{tr}_x$ is the speed of the tractor (in m/s), $l_{pót} + l_k$ is the distance of the axles of the tractor and the trailer (in meters).

The actual value of the pulling angle in differential equation form:

$$\frac{1}{A}\frac{d\gamma_{din}}{dt} + \gamma_{din} = \gamma_{stat} \tag{8}$$

The solution of the equation depends on the input function ($\gamma_{stat}$). Using step input function with the amplitude of $\gamma_{stat}$, the equation of $\gamma_{din}$ output will be:

$$\gamma_{din} = \gamma_{stat}\left(1 - e^{At}\right). \tag{9}$$

### 2.2.3. Determination of the yaw motion

Yaw motion: the rotational speed or angular speed of the vehicle around its vertical axle. Notation: $\psi$ (1/s or radians/s).

If a vehicle travels on a circle of *r*-radius (m) with *v* speed (m/s), then it requires *T* time (s) to take a whole round. The road traveled is *2rπ* (m) and the speed of the vehicle is:

$$v = \frac{2r\pi}{T} \quad \left(\frac{m}{s}\right) \tag{10}$$

The yaw motion speed:

$$\psi = \frac{2\pi}{T} \quad \left(\frac{rad}{s}\right) \tag{11}$$

Combining equations 10 and 11 the yaw motion speed can be calculating as follows:

$$\psi = \frac{v}{r} \tag{12}$$

Using notations of Figure 4:

$$\psi = \frac{v_x^{tr}}{r_B} \tag{13}$$

This equation serves then for the determination of the expected value of the yaw motion of the tractor. As in equation 5 it has been introduced:

$$r_B = f(\delta, \text{geometry}, v), \tag{14}$$

The following conclusion from the yaw motion of the tractor can also be drawn: it is a function of speed, steering angle and the geometry.

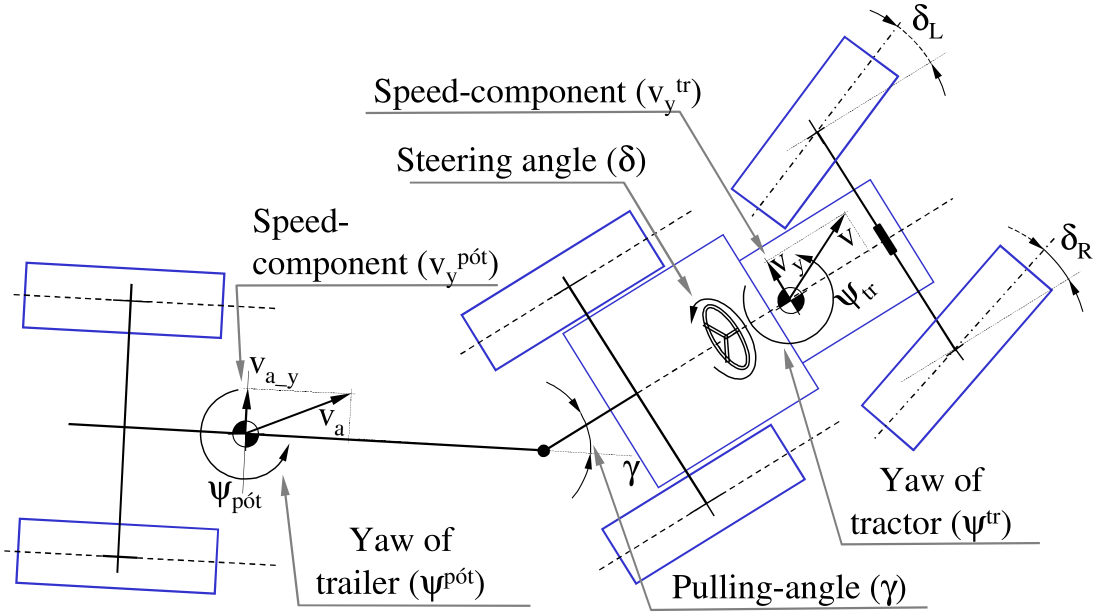



**Figure 4: Notations used in the description.**

### 2.2.4. Comparison of steering angle and side speed

This method based on the comparison of the sign of the side speed component of the vehicle with the sign of the steering angle. In stable state the signs are identical In case of trailers the sign of the steering angle is substituted with the sign of the pulling angle. Trailer side sliding and tractor oversteering can be confirmed by this method.

### 2.2.5. Stability programs

The stability programs are logical functions of which value is 0 if the vehicle behaves as expected, and 1 if instability is detected.

The general form of the criteria equations is:

$$stab = \begin{cases} 0, if\ \exp ected < \exp ected_{\min} \vee measured \in \left[\exp ected_{low} \ldots \exp ected_{high}\right] \\ 1, if\ \exp ected > \exp ected_{\min} \wedge measured \notin \left[\exp ected_{low} \ldots \exp ected_{high}\right] \end{cases} \tag{15}$$

where:

- expected is a the calculated value of the stability determining parameter.
- $\text{expected}_{\text{min}}$ threshold value of the expected parameter. If measured lower is expected, then no stability validation is done,

- $expected_{low}$ the lower limit of the reference band used in the comparison of expected and measured values,
- $expected_{high}$ the upper limit of the reference band used in the comparison of expected and measured values,

The concrete criteria equations of the three stability programs:

Yaw-motion method:

$$stab_v = 1\Big|_{\psi_e > \psi_{min} \wedge \psi \notin \left[\left(1-k_\psi\right)\cdot\psi_e \ldots \left(1+k_\psi\right)\cdot\psi_e\right]} \tag{16}$$

In this case the reference band is in $k_\psi$ distance around $\psi_e$ expected yaw motion speed.

Pulling angle method:

$$stab_p = 1\Big|_{\gamma_{din} > \gamma_{min} \wedge \gamma \notin \left[\left(1-k_\gamma\right)\cdot\gamma_{din} \ldots \left(1+k_\gamma\right)\cdot\gamma_{din}\right]} \tag{17}$$

In this case the reference band is in $k_\gamma$ distance around $\gamma_{din}$ expected pull angle.

Sidespeed method

$$stab_v = 1\Big|_{v_y > v_{y\_min} \wedge \delta \cdot v_y < 0} \tag{18}$$

### 2.2.6. Warning and intervening system

Based on the stability checking methods described in the previous chapters, I have created a warning and intervening system. The warning system can warn the driver about the instability detected on the vehicle, and the risk of an upcoming accident. This system takes action when the stability parameter falls outside the reference band around the calculated expected value. The reference band can be determined in different ways. Its width can be constant or function of the reference signal value. The correct selection of the reference band is an important factor of the quality of the stability control system.

The reference bands of the intervening system can differ from the one of the warning system. I recommend using a narrower reference band for the intervening system. The reason for this is that the warnings, if they come too often, will be ignored by the driver, and which can cause problem in case of serious loss of stability.

## 2.3. Validations by field measuring

I have done the validations by a domestic made SR-10 type forwarder used in the forestry attached to a Landini Landpower tractor.

The data of the vehicle train:

Type of the trailer SR-10 forwarder

Wheels: 4ps Mitas 405/70 R20 MPT-01

Self weight: 5400 kg,

Weight of the cargo: 4200 kg

Type of the tractor: Landpower Landini 135 TDi

Rear whels Kleber Fitker 520/70 R38

Front wheels Kleber Fitker 420/70 R28

Mass: 5600 kg

Axle distance: 2800 mm

Wheelbase front: 2014 mm

Wheelbase rear: 2014 mm

Total length: 5143 mm

### *Combined braking and steering test*

The test has been performed on a pre-determined test track, which is detailed in Figure 5. The track has 2 stages. The first stage is a leading up stage, which is for achieving steady state states of motion, and the second is for a constant braking stage till still stand. In the second stage there were 4 different steering angle setting (a-d variations in the figure).

The goal of the test is to determine the accelerations, wheel slips and curving stability during the braking and combined braking and steering.

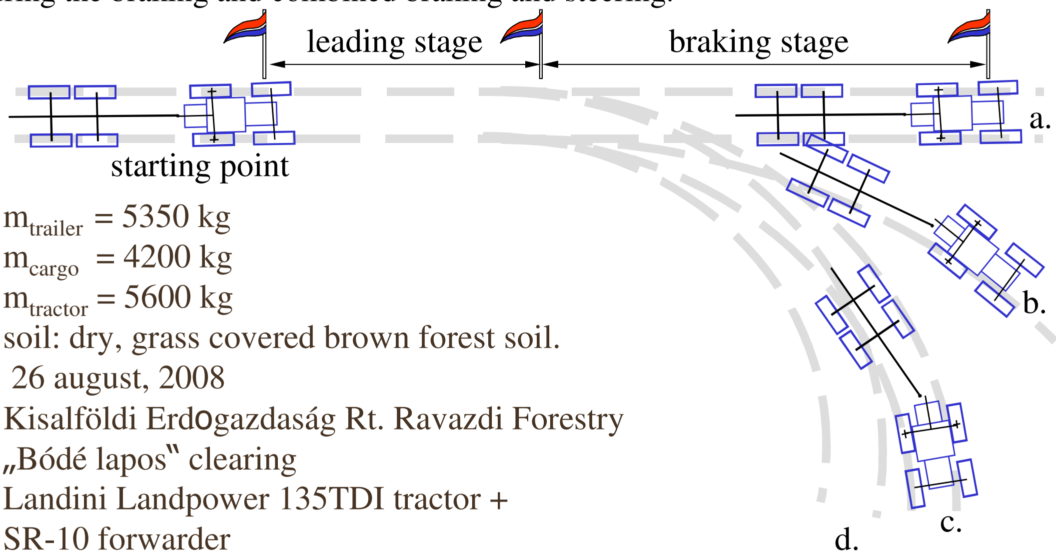



**Figure 5: Measuring stages of the combined braking and steering test**

***Roundabout test***

One of the stability programs based on measuring the pulling angle between the tractor and the trailer. The roundabout test id to validate the determination of the expected value of the pull angle in steady and transient states.

***Validation test***

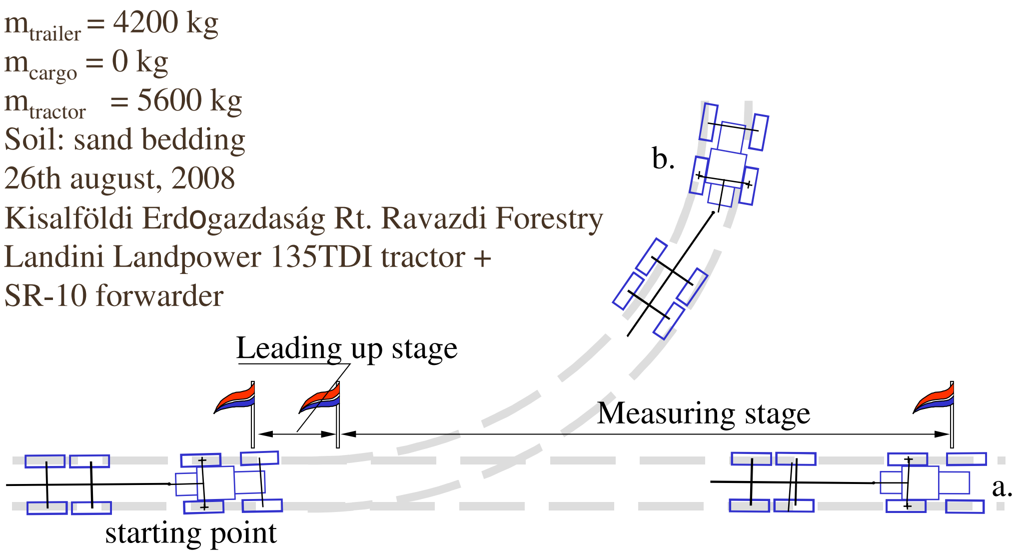



**Figure 6: Plan and data of the validation test**

The validation tests were performed in an empty barn, which were under construction. The barn had fine sand, leveled bedding, which appeared ideal and easily reproducible. In the bedding I have marked a short stage to achieve a near steady-state running of the vehicle combination, and a 20 meters long straight ahead track, and a left turning one. (Figure 6 a and b).

# 3. PROCESSING THE MEASURING DATA AND RESULTS

## 3.1. Processing of the measured data

Braking test:

The vehicle-train after a pre-stage travels further to the second stage either straight ahead, or taking a turn with the steering wheel turned to 7, 15 or 18 degrees, while in the same time decelerates by applying the brakes smoothly. The measuring is continued till still-stand of the vehicle. During the measuring the steered-wheel angle, the pulling angle, the accelerations of the vehicle bodies, were recorded by data acquisition system, and the number of the rotations of the wheels, and the time required to pass stage 1 and 2, the speed of the tractor, and a trigger signal were recorded manually. Having the first series of measuring done, two similar sets of measuring followed.

### 3.1.1. Processing and evaluating the control measuring data

Table 1 shows the manually recorded, and the calculated data based on the manually recorded ones, and the file identification codes, which are for pairing the manually and the electronically recorded data.

**Table 1: Manually recorded and calculated data of the control measuring.**

| Code | file | δ | T | $n_b$ | $n_j$ | $v_h$ (km/h) | $l_b$ | $l_j$ | $s_b$ | $s_j$ | $l_{b0}$(m) | $l_{j0}$(m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | | 0 | | | | 10.00 | - | - | (1.00) | (1.00) | 19.00 | |
| B2 | 10.29 | bal | 20.00 | 3.25 | 3.50 | 3.70 | 17.77 | 19.13 | 0.05 | 0.04 | 17.00 | 18.40 |
| B3 | 10.30.54 | 0 | 21.00 | 4.25 | 4.50 | 3.70 | 23.23 | 24.60 | 0.01 | 0.07 | 23.00 | |
| B4 | 10.37.50 | bal | 20.00 | 3.25 | 3.75 | 3.70 | 17.77 | 20.50 | 0.05 | 0.11 | 17.00 | 18.40 |
| B5 | 10.40.38 | 0 | 22.00 | 5.00 | 5.00 | 3.60 | 27.33 | 27.33 | 0.19 | 0.19 | 23.00 | |
| B6 | 10.42. | 0 | 21.00 | 4.75 | 4.75 | 3.60 | 25.97 | 25.97 | 0.13 | 0.13 | 23.00 | |
| B7 | 10.43.35 | bal | 17.00 | 3.50 | 3.75 | 3.60 | 19.13 | 20.50 | 0.13 | 0.11 | 17.00 | 18.40 |

Annotations:

*Set data:*

δ: steering angle: $0^o$: straight, left: a left turn with $30^o$ steering angle.

*Manually recorded data:*

T time required to pass the measuring track (s)

$n_b$, $n_j$ Number of rotations of the driven wheels. (left and right tire accordingly at the whole track)

*Calculated data:*

$l_b$, $l_j$ road traveled by the left and right driven wheels. (m)

$s_b$, $s_j$ slip of the wheels (left and right, m)

$l_{b0}$: length of the measuring track (measured at the left wheel, m)

$l_{j0}$: length of the measuring track (measured at the right wheel, m)

Figure 7 shows the measured data of the set marked by B4 after post processing. The post processing were done by averaging the data recorded in one thousands seconds in every one tenth seconds, which corresponds to a 10Hz low-pass filter. The $t_0$ notation on the picture shows the trigger signal.

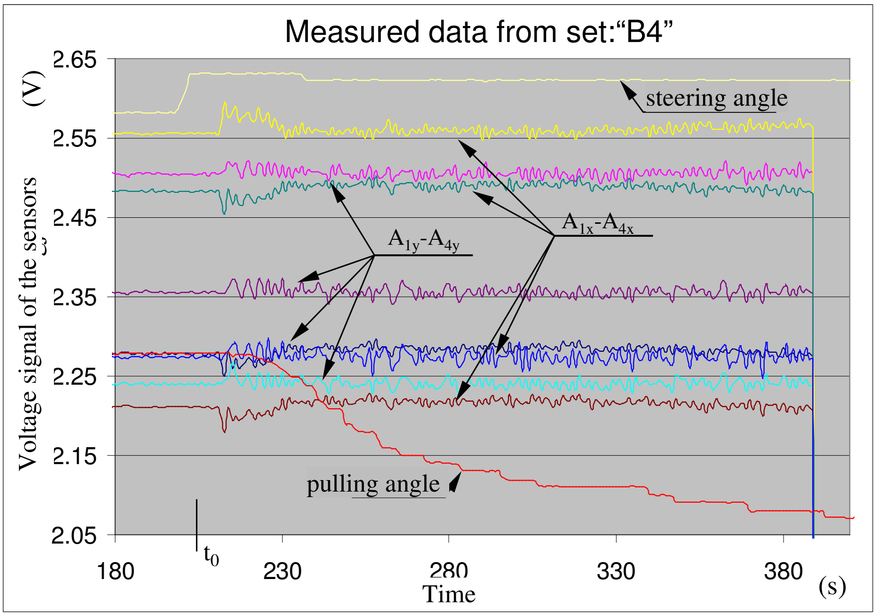



**Figure 7: The recorded acceleration, and angle data of the B4 control measuring after post-processing.**

### 3.1.2. Evaluation of the braking and steering test

The measuring was performed in the land of the forestry of Kisalföldi Erdőgazdaság Rt. at the Ravazdi Erdészet location. The measuring was performed in accordance with a pre-determined plan, described in chapter 2.3. The measuring track is shown in the Figure 5. The steady-state stage is 30, the braking stage is also 30 meters, long. The steering angles are from a to d 0, 8, 18, 23 degrees (measured on the front left wheel.

The measuring were performed on a dry sunny day, ambient temperatures were 20-23°C. The soil was a brown forest soil, permanently maintained, plant covered clearing.

During the measuring data was partially manually and electronically recorded. The measuring sets became a code for further pairing the corresponding manually and instrumentally recorded data.

The manually recorded, and the calculated data is summarized in the table 2.

Codes beginning with F indicate data measured at the braking and steering data, codes with H indicating the data of the roundabout test.

**Table 2: Field measuring data of braking and steering (F) and roundabout (H) tests**

| Code | $\delta_e$ | $\delta$ | $\gamma$ | $t_1$ | $t_2$ | $n_b$ | $n_j$ | $v_h$ | $l_b$ | $l_j$ | $s_b$ | $s_j$ | lb0(m) | lj0(m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F10 | 0 | 0 | 0 | | | | | 18 | 0.00 | 0.00 | -100.00 | -100.00 | 32 | 32 |
| F10a | 0 | 0 | 0 | | | | | 12 | 0.00 | 0.00 | -100.00 | -100.00 | 32 | 32 |
| F10b | 0 | 0 | 0 | 12.79 | 23.41 | 12 | 12 | 10 | 37.70 | 37.70 | 17.81 | 17.81 | 32 | 32 |
| F11 | 8 | 7.2 | 10 | 13.38 | 25.03 | 9.5 | 8.5 | 10 | 29.85 | 26.70 | 10.54 | 11.26 | 27 | 24 |
| F12 | 18 | 17 | 21 | 14.5 | 24.45 | | | | 0.00 | 0.00 | -100.00 | -100.00 | 23 | 20 |
| F13 | 23 | 22 | 29 | 14.45 | 26.16 | 8 | 7 | 10 | 25.13 | 21.99 | 32.28 | 46.61 | 19 | 15 |
| F20 | 0 | 0 | 0 | 14.42 | 23.25 | 12 | 12 | 10 | 37.70 | 37.70 | 17.81 | 17.81 | 32 | 32 |
| F21 | 8 | 9 | 12 | 14.5 | 28 | 10 | 8.25 | 10 | 31.42 | 25.92 | 16.36 | 7.99 | 27 | 24 |
| F22 | 18 | 17 | 22 | 12.6 | 28.78 | 8.75 | 7.75 | 10 | 27.49 | 24.35 | 19.52 | 21.74 | 23 | 20 |
| F23 | 23 | 23 | 30 | 18.41 | 33.84 | 7.5 | 6.25 | 10 | 23.56 | 19.63 | 24.01 | 30.90 | 19 | 15 |
| F30 | 0 | 0 | 0 | 15.32 | 23.31 | 12 | 12.3 | 10 | 37.70 | 38.48 | 17.81 | 20.26 | 32 | 32 |
| F31 | 8 | 8 | 11 | 14 | 27.8 | 9.75 | 8.25 | 10 | 30.63 | 25.92 | 13.45 | 7.99 | 27 | 24 |
| F32 | 18 | 19 | 22 | 14.51 | 27.22 | 8 | 7.75 | 10 | 25.13 | 24.35 | 9.27 | 21.74 | 23 | 20 |
| F33 | 23 | 26 | 32 | 16.98 | 30.35 | 7 | 6 | 10 | 21.99 | 18.85 | 15.74 | 25.66 | 19 | 15 |
| F40 | 0 | 0 | 0 | 14.8 | 25.2 | 13 | 12 | 10 | 40.84 | 37.70 | 27.63 | 17.81 | 32 | 32 |
| F41 | 8 | 10 | 13 | 14.73 | 29.13 | 10 | 8.5 | 10 | 31.42 | 26.70 | 16.36 | 11.26 | 27 | 24 |
| F42 | 18 | 17 | 22 | 13.1 | 28.85 | 8.5 | 7.75 | 10 | 26.70 | 24.35 | 16.10 | 21.74 | 23 | 20 |
| F43 | 23 | 23 | 31 | 13.39 | 24.53 | 6.5 | 5.5 | 10 | 20.42 | 17.28 | 7.48 | 15.19 | 19 | 15 |
| H1 | 0 | | | 47.39 | | | | 2.5 | 0.00 | 0.00 | -100.00 | -100.00 | 32 | 32 |
| H2 | 23 | 23 | | 29 | | 12.3 | 8 | 2.5 | 38.48 | 25.13 | | | | |
| H3 | 23 | 23 | | 29 | | 12.8 | 9 | 2.5 | 40.06 | 28.27 | | | | |

Annotations:

*Set data:*

δe: steering angle: ($^o$)

$V_h$: vehicle speed (m/s)

*Measured data:*

δ: steering angle: ($^o$)

γ: pulling angle ($^o$)

*Manually recorded data:*

$t_1$ time required to pass stage 1 (s)

$t_2$ time required to pass stage 2 (s)

$n_b$, $n_j$ number of rotation of the driven wheels of (on left and right side accordingly)

Ca*lculated data:*

$l_b$, $l_j$ road traveled by the left and right driven wheels. (m)

$s_b$, $s_j$ slip of the wheels (left and right, m)

$l_{b0}$: length of the measuring track (measured at the left wheel, m)

$l_{j0}$: length of the measuring track (measured at the right wheel, m)

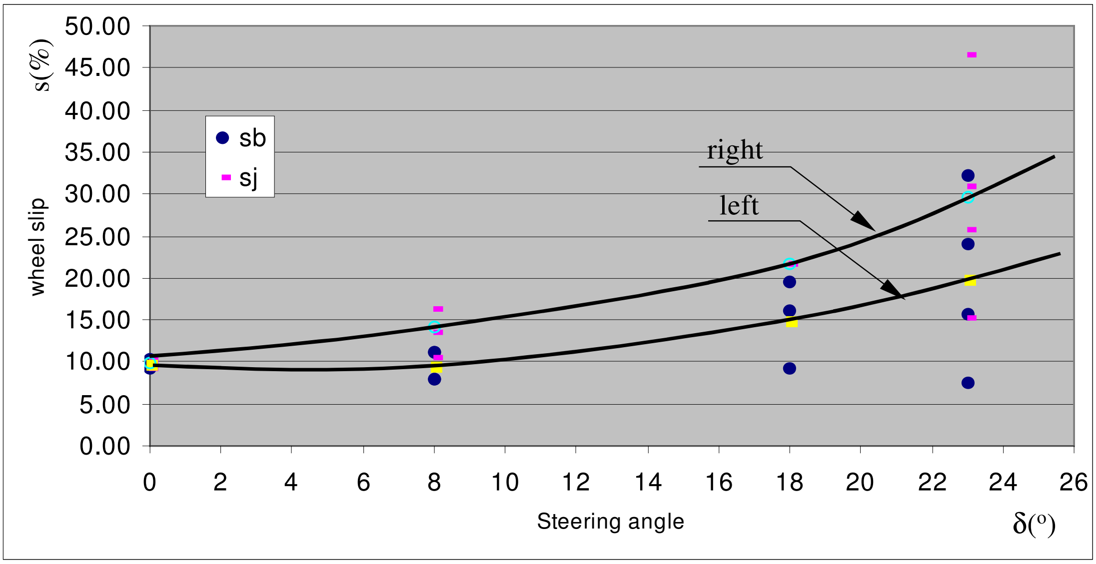



**Figure 8: Wheel slips as function of steering angle**

Figure 8 shows the dependency of the slip of the driven wheels as a function of the steering angle. The corresponding point pairs were calculated from data of table 2. The continuous line is a tendency curve drawn over the average calculated slip at the set steering wheel angles. It can be seen, that the slip differentiates between inner and outer wheels in the respect of turning direction. The slip of the inner wheel is proportionally greater than the outer, depending on the steering angle. The averages of the slip values are raising proportionally with the steering angle. Its reason is that the traveling losses are increasing with the steering angle, and the increased losses are indirectly cause increasing slip values.

### 3.1.3. Evaluation of the roundabout test

The goal of the roundabout test is to bring the vehicle train in extreme state in order to validate the stability program, and the calculation method of the pulling angle. During the test only the trailer drive was used wit the steering angle set in 28 degrees to the right.

Data recorded during the test were:

- Numbers of rotations of the trailer tires ($n_b$, $n_j$)
- Accelerations of the trailers body ($a_{A1x}$- $a_{A4y}$)
- Steering angle ($\delta$)

- Pulling angle ($\gamma$)
- Traveling speed of the train ($v_h$)

From the recorded data of H2 measuring I took and processed the steering and pull angle data. I have created the computer model of the vehicle train, and set the parameters in accordance with the measured vehicle. Using the recorded speed and steering data, I have reproduced the simulation with the model. The pull angle produced by the simulation then was compared with the measured one. (Figure 10), which after I draw the following conclusions.

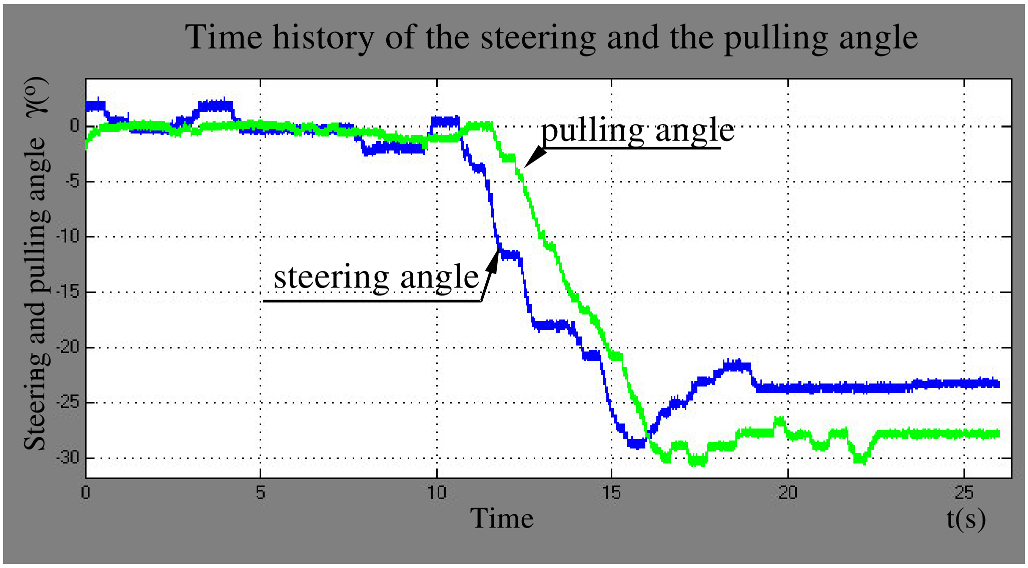



**Figure 9: Time history of measured steering and pulling angles**

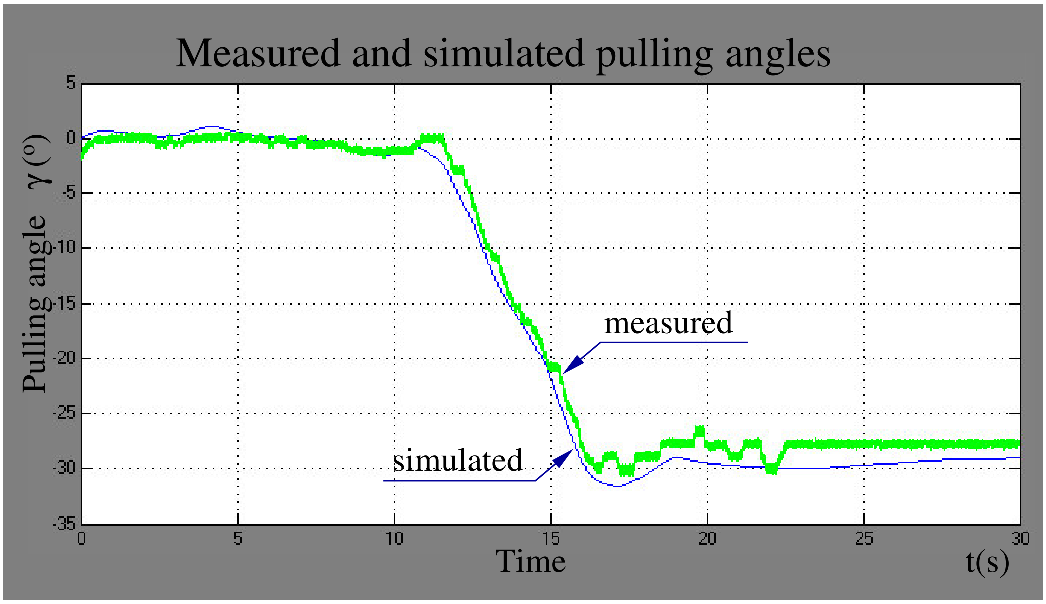



**Figure 10: Comparison of measured and simulated pulling angle**

Figure 9 shows the time history of the recorded steering and pulling angles, which were used as input of the simulation and comparison base in the validation.

Figure 10 shows the result of the comparison of the measured and simulated pulling angles. It can be seen that the simulation curve approaches satisfactory the measured one.

## 3.2. Data gained from simulation of the vehicle train

During computer simulations information about the dynamical behavior of the vehicle train vas gained. Data gained in this way are marked in the diagrams by "simulated" Parallel with the determining the vehicle dynamic properties, a reference model was also running to determine expected values of the stability determining parameters for the stability programs. Such parameters are sigh of side-speed, yaw motions, pulling angle. Data determined by the reference model ara marked by "calculated". In a vehicle equipped by stability program, the simulated data will be replaced by measured data from a data acquisition system, and the calculated data will be gained by an on-board model. The two data will be then used for distinguishing stable state of the vehicle from the unstable.

**Recreating stability of a vehicle from unstable state.**

The easiest way to bring an instable vehicle back to stable is to decrease its speed by decreasing driving torque.

The proofing I have done by using the vehicle model. For this goal I have created a vehicle model of an agricultural tractor and a propelled axle trailer. The speed of the vehicle and the steering angle was set so, that the vehicle train will likely start skidding.

In order to determine the need and the way of the intervention, I have worked out different strategies.

The inequality of measured and expected values of stability determining parameters are taken into consideration when the measured value is outside a tolerant band around the expected value.

Determining the width of the tolerant band requires special attention, while too narrow band will result too frequent and most often false warnings of which can easily be ignored by the drivers. A too wide band will let too little time for intervention in care of a real hazardous state. It is practical to determine the tolerant band as a function of speed so that it is narrower at lower, and wider at wider speeds.

For the intervention there are more possibilities. The speed reduction can be done either by reducing the wheel torque, or applying the brakes. With selective braking counter yaw motion can be achieved which can restore stability in some cases. The easiest to perform is the reduction of motor torque, and this is the one, which can be the most easily built in posteriori.

The reduction of the motor torque can be done continuously or in several steps.

In the simulated accident the speed reduction was done in a one step torque reduction.

First I have brought the model vehicle in an unstable situation, which in real situation would result in a serious accident. Then I have studies the procession of the accident.

After that I have enabled the stability program, and performed the same driving situation, as before, and examined the effect of the stability program on the vehicle's behavior.

Figure 11 shows the time history of the simulated and calculated values of the pulling angle. It can be seen that the pulling angle does not deviate from the expected more than a certain limit. It means that the vehicle remained stable.

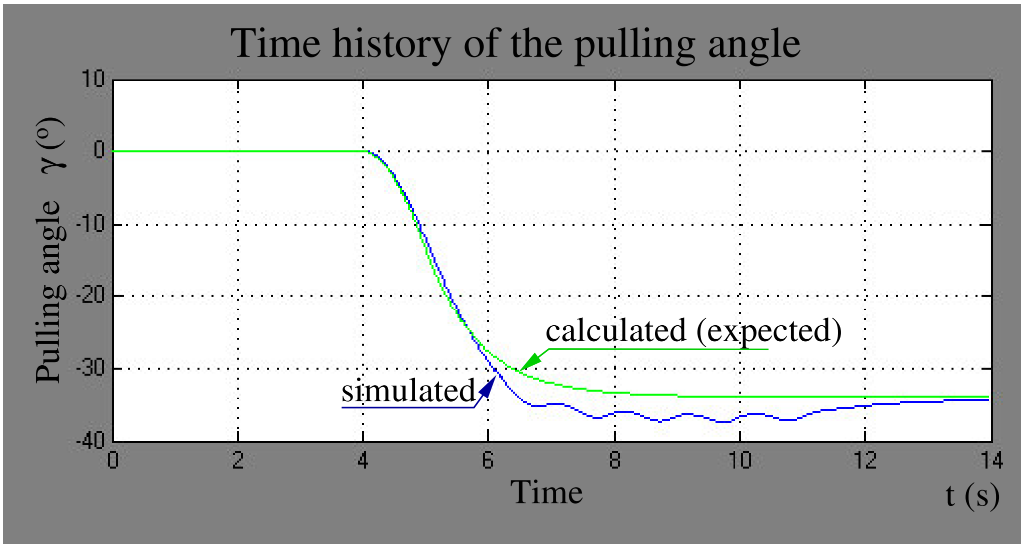



**Figure 11: Time history of the pulling angle of the stabilized vehicle train**

Examining the accidents with different speed and steering angle I have concluded that the side sliding of the trailer at an early stage can be stabilized by reducing the driving torque.

# 4. THESES

1 I have made the Ackermann conditions of steering provenly more exact by extending it to vehicle combinations. By this besides the wheel angles, another important factor of the curving stability, the steady state value of the pulling angle can also be determined.

The equation, which I have set up, and proved for determining the steady state value of the pulling angle is:

$$\gamma_{stat} = \arctan\left(\frac{l_k}{r_B}\right) + \arcsin\left(\frac{l_{pót}}{\sqrt{(l_k^2 + r_B^2)}}\right)$$

where: $$r_B = \frac{l_{tr}}{\tan(\delta_L)} + \frac{w_A}{2}$$

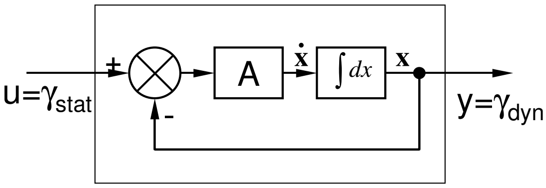
2 I have determined the transient function of the pulling angle, which gives the $\gamma_{din}$ dynamic pulling angle as the function of geometry of the vehicle, steering angle and vehicle speed.

The transient function of the pulling angle can be determined by the following differential equation:

$$\frac{1}{A}\frac{d\gamma_{din}}{dt} + \gamma_{din} = \gamma_{stat}$$

The solution of the equation depends on the input function. In case of a step function with $\gamma_{stat}$ amplitude the solution of the differential equation will be $\gamma_{din} = \gamma_{stat}\left(1 - e^{At}\right)$, where *A* is a coefficient, which value depends on the vehicle speed, geometry and has a (1/s) dimension.

The block scheme of the equation is:




This model in a numeric way can produce the pulling angle output for any steering wheel input function. Knowing the current expected value of the pulling angle is one of the most important factors of determining the vehicle's stabile state.

3 I have proved that the stability determining method based on measuring the pulling angle is able to determine under and oversteering conditions of the vehicle train. With this the steering anomalies of the agricultural transport systems can be solved.

This method determines the expected value of the pulling angle from the geometry of the vehicle and steering angle, and then compares it with the measured one. From de volume and the sign of the deviation the method determines neutral, under or oversteering state of the vehicle.

I have concluded and proved by means of calculations that in case of a vehicle trains the ground parameters of a stability program can be the yaw motions and side speeds of the vehicles, and the pulling angle.

4 I have concluded and proved by means of measuring that in case of a vehicle trains the most reliable stability determining method is the one which based on measuring the pulling angle. The method based on measuring the yaw motion was also adequate, but to measure and evaluate yaw motion appeared to be more difficult that measuring the pulling angle. Sign of the side-speed method was not able to recognize all the examined instability situations of the vehicle train, and also signaled later than the other two, but it can be used to confirm hazardous driving state of the vehicle.

I have created different algorithms in order to fulfill the requirements of the stability programs, and I have validated them by means of calculations.

I have created a warning algorithm, and set up the criteria equations of vehicle state in order to detect vehicle state, and give a warning signal in case of instability detected. The warning system has been laid out so that it gives a possible minimum number of false signals, but leaves time enough for intervention in case of real instability.

**Possible practical usage of the results:**

The practical gain of the stability program developed for the agricultural transport vehicles is the possible increase on safety of the present systems. The program can be subsequently mounted on the vehicles as a warning or warning and intervening system.

Further advantage of the stability control system is that by then that criteria the propelled axle trailer can only be used when axle drive has a control system also fulfilled.

The models I have created has been planned so that they can be used for modeling other kind of vehicle dynamical problems, or can be used for the education. Such other problem can be the rollover of the vehicle, or developing an ABS or ASR system for the transport vehicles.

# 5. CONCLUSIONS, RECOMMENDATIONS

Using propelled axle trailers on the agricultural transport system can increase energy efficiency and mobility, and decrease on soil damage. Trailer axle drive can only be use with adequate drive control system, which can prevent jackknifing of the train, and ensures optimal drive torque distribution.

I have concluded during the literature research that the control of tractor-trailer combination systems has ample literature, but majority of it deals with systems travelling on covered surfaces. Besides this, majority of the literature using a too simplified model description, which is not adequate to describe motion of the vehicle over a terrain surface.

During the measurements performed on the test vehicle combination, the vehicle remained stable even at the most demanding conditions. Jack knifing, side slipping did not occur. Its main reason is the low speed, low inclination and the stable construction of the vehicle. There may be need for a measurement, where unstable state of the vehicle can be generated, so that the stability program (intervening and/or warning system) can be validated in real situation.

The yaw motion and the side slipping of the vehicle has been determined indirectly, by acceleration measuring. By this method it could although the required values be determined, but a direct measuring of the required data (e.g. by yaw sensor) would give better base on the stability determination program, thus more exact operation.

The method based on the pulling angle performed well without any difficulties in the validation test measuring, the signal-noise ration was a lot better than in the case of the yaw and side slipping methods. The pulling angle measuring consisted of mechanical components, so it requires maintenance and has a higher possibility of failure.

The model park can be further developed in order to make it able to perform modifications from a menu system. This would enable the program to be used by persons without programming knowledge.

The function minimum location identification program can identify the parameters of the multi-parametric tire force function based on field measuring data.

The selected and modified tire force model together with the parameter identification program proved to be a well usable model for the task.

# 6. SUMMARY

In the recent decades a tendency can be observed in which the capacity and travelling distance of the agricultural transport vehicles are increasing. The expectation relating to agricultural transport systems are increasing as well. The transport vehicles in regard of soil compaction and air pollution have to be as environmental safe as possible, while on solid surface roads they have to be able of travelling energy efficiently ad as fast as possible.

In both questions of energy efficiency and mobility the solution can be the usage of propelled axle trailers for the agriculture and the forestry as well.

The usage of propelled axle trailers are not new. The widespreading of the technology is hurdled by the fact that the control of the trailer protrusion is not yet worked out in a sufficient level. Earlier solutions ended up in serious, often fatal accidents, while in special fields, like the forestry they remained in the production.

The recent development of vehicle control and stability systems brought the question of re-entering the propelled axle trailers in the agricultural transport up again. With the tools available today the stability of the transport systems can be ensured by detecting and solving unstable vehicle states.

In my thesis I deal with the process of accidents related to agricultural transport systems consisting of tractors and propelled axle trailers, as well as stability measuring methods.

I have created a model park, which is capable of running vehicle dynamic related simulations primarily in order to develop vehicle train stability programs. I have looked for parameters which are capable to distinguish vehicle train's stable state from unstable. I have also worked out stability programs and examined their usability.

I have compared the simulation results with measured results acquired from propelled axle transport system on order to validate the model park, and the reference parameter calculating methods

During the development of the model park I have considered the flexibility of the models for being able to use them for different other simulation purposes. In this way they have been constructed in a modular basis, I have created user interface and animation capability. Further aspect was to make the model able of being used in the higher education.

# 7. LIST OF PUBLICATIONS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