

## **WHEEL LOAD MEASUREMENT, WIM, ACCURACY, TOP TRIAL**

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### **ABSTRACT**

The article focuses on methods for the design of WIM - sensor fields and algorithms for evaluation of dynamic axle load measurement data developed in the TOP TRIAL project.

Design methods and evaluation algorithms aim to increase measurement accuracy of dynamic weighing systems and to reliably determine static axle loads and gross vehicle weights with a high degree of precision.

Introduced are simulative, graphic and numerical methods for calculating and designing WIM sensor fields to minimize dynamic axle load variations measurement errors.

The various methods of calculation and design are based on deterministic as well as stochastic 1- and 2-sinusoidal wave approaches for modelling actual dynamic gross vehicle weight and axle load vibrations. The error minimization methods developed are based on the use of mean value and tolerance interval methods as well as the curve fitting method.

All methods introduced have been programmed and tested under real-life conditions.

### **1. TOP TRIAL PROJECT**

The TOP TRIAL project, executed in the European Commission 5<sup>th</sup> Framework programme deals mainly with automated truck (overload) control and generation of enforcement rules for harmonization.

TOP TRIAL project partners are:

- Bauhaus-Universität Weimar
- Bundesanstalt für Straßenwesen, Bergisch Gladbach
- Bundesministerium für Verkehr, Bau- und Wohnungswesen, Bonn
- ETH Zürich
- Instituto das Estradas de Portugal, Lisboa
- Ministry of Transport Public Works and Water Management, Delft
- mit Autobahndirektion Südbayern, München
- Oberste Baubehörde im Bayerischen Staatsministerium des Innern
- PAT GmbH, Ettlingen
- Polizeipräsidium Oberbayern, München
- Produtos para Analise e Controlo de trafego, Oporto
- PTV Planung Transport Verkehr AG, Stuttgart
- Rigobert Opitz Consulting & Engineering, Malsch

TOP TRIAL info: 1)Web: [www.TOP TRIAL.de](http://www.TOP TRIAL.de); 2)E-Mail: [kontakte@TOP TRIAL.de](mailto:kontakte@TOP TRIAL.de)

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### **2. TOP TRIAL TECHNICAL PROJECT DESCRIPTION**

#### 2.1. Overview

Overloaded heavy vehicle traffic implies a considerable safety risk for other road users. The objective of the TOP TRIAL project is to create the preconditions for an increased traffic safety and an improved protection of the road

infrastructure by new technologies and methods of automated truck overload control. The solution worked out within the framework of the TOP TRIAL project, combines the currently two suitable weighing technologies for truck axle loads (bending plates and crystal sensors) in a simulatively tested multi-sensor array. Efficient heavy vehicle control on automatic weighing stations to enforce overloads on motorways means:

- protection of the road infrastructure from damage
- improved traffic safety and less traffic incidents
- fair competition for fleet operators
- cost savings and efficiency by means of direct control on site without staff

## 2.2. Top Trial Objectives

The first step of the TOP TRIAL project was to agree on the following objectives:

- development and construction of a optimised test site for "High-accuracy Staggered Multi-sensor Arrays" for dynamic weighing of heavy vehicles and overload enforcement
- to implement WIM experiences in an usable approach: simulated and optimised sensor configuration – use of twin WIM technology– sparsely coded and
- operation of the test system on a highly frequented motorway under real traffic conditions using more than thousand random overloaded truck probes
- development of measurement improvement algorithms for automatic WIM
- preparation of technical requirements, procedures of automated controlling truck overloads and initiation of a European Forum „Weigh-in-Motion for Enforcement“
- organization of an international workshop Munich 2002 on overload control

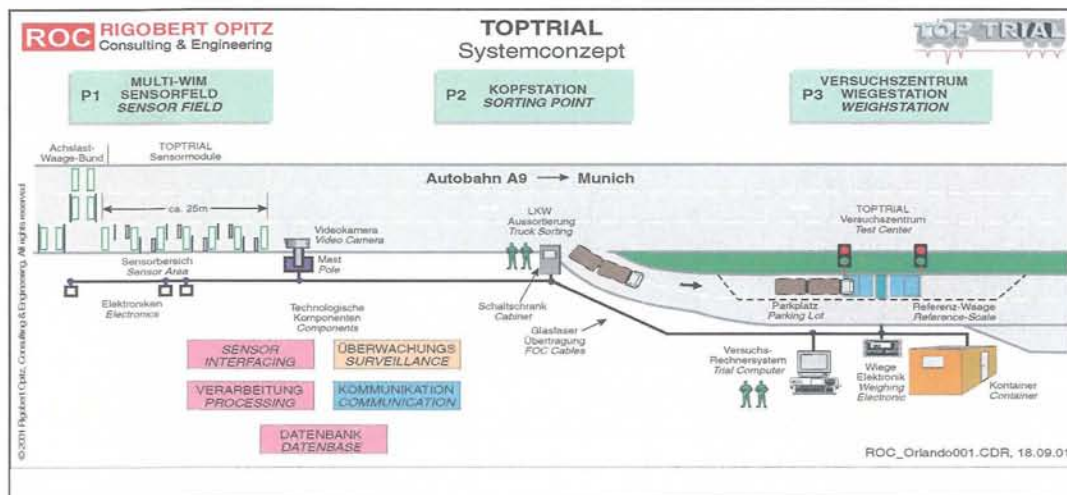


Figure 1 -TOP TRIAL System Concept

## 2.3. Top Trial System Concept

The overall TOP TRIAL test system includes 3 major components located in an area of 3 km along the Autobahn A9 in Germany, interconnected via a high speed communication system.

The conceptual studies and the simulation analyses finally led to TOP TRIAL sensor configuration consisting of 16 sensors. The weighing sensors of the multi-sensor, sparsely coded twin technology array have been installed in an area of approx. 25 m on the right lane of the Autobahn A9 near Ingolstadt. All passing heavy vehicles are weighed dynamically at ordinary speed. A video camera takes front pictures of overloaded trucks and sends them to the sorting point and the trial container. The weighing electronics record the signals of the sensors and preprocess them. All vehicle details are transmitted to a database and later combined with the data of a static reference scale system.

A special concrete area and a reference scale located on a parking lot 2km behind of the test site was designed and installed. The calibrated axle load weighbridge is used in slow motion in order to provide accurate axle loads as a basis for comparison with the calculations by the algorithms. The best algorithms are analyzed.

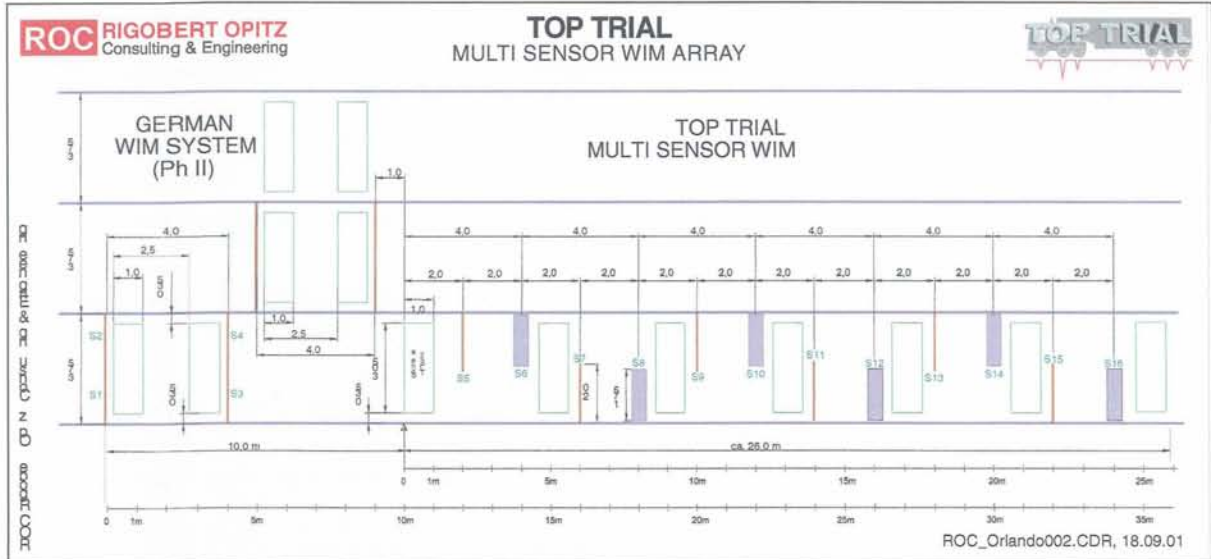


Figure 2 - Detailed Sensor Layout Drawing Optimized by Simulations



Figure 3 – Reference and Enforcement Scale.- Designed as Dynamic Axle Weighbridge

### 3. SCIENTIFIC ANALYSIS OF SENSOR ARRAYS AND DESIGN OF ALGORITHMS

#### 3.1. Simulation and Construction

Part of the project was the analysis and simulation of the best sensor field combination on a scientific base. Different researches and the design of special simulation tools (by the Bauhaus-University Weimar) supported the optimisation of the layout of the sensor array. Key issues of these research work were:

- Design of algorithms for the minimisation of measurement errors of dynamic weight measurements by the use of multi-sensor WIM systems
- Simulative design of the sensor array with “minimum” measurement errors

Basic literature of this work is:

- 'Design of multiple-sensor weigh-in-motion systems' [1],
- 'WAVE-project' [2],
- 'Measurement and analysis of dynamic tyre forces generated by lorries' [3] and others.

This literature describes the sinusoidal wave approach which we considered to be a possible theory for creation and validation of WIM-sites.

The sinusoidal wave approach is not a very sophisticated one for studying vehicle/pavement interaction, however it still has some scientific potential.

The main objective of the 8<sup>th</sup> man month TOP TRIAL project was a usable runtime version and not a high sophisticate solution.

It was intended to use the potential of the sinusoidal approach for construction of WIM sites as well as for validation of measurement data.

Therefore the existing sinusoidal wave approach was extended by a 2-sinusoidal wave model and an optimisation tool for minimising error deviation which is based on a sinusoidal wave model too in order to get a consistent solution for construction and validation of data.

Furthermore an increasing of measurement accuracy was expected by the use of suitable sinusoidal based algorithms such as curve fitting algorithms.

Second objective of TOP TRIAL was a minimum cost at a minimum number of the sensors used in the WIM array.

Most of the man month were planned to develop algorithms for validation test data. (All experiences made during the TOP TRIAL project have shown that this was right as the parallel developing of algorithms, gathering of measurement data and calibration of sensors caused a lot of efforts. Due to the permanently changing conditions of the weighing technology algorithms had to be adapted often.

For more efficient use of the construction/algorithms complex load frequency and speed of the traffic flow are a necessary inputs.

Additional to the methods described in literature the construction method which was developed allows to take the distributions of these parameters into account and calculates optimum sensor distances.

Finally the developed algorithms for validation of measurement data test the sensor outputs whether they are sinusoidal waves or not. If data is tested positive, static loads will be calculated, otherwise it is rejected.

During the TOP TRIAL project 2 digital simulation tools were created allowing generation of WIM sensor fields in substantial diversity and determination as well as comparison of important qualitative and quantitative parameters. These tools also enable simulations of dynamic axle load oscillations of actual vehicles featuring highly detailed characteristics so the influences of real parameters on to the sensor layout could be estimated.

Especially the interrelations between speed, load, type, frequency, dynamic load amplitude and other factors are more or less unknown and could be analysed using the simulator in combination with specific mathematical tools.

With the first simulator a great diversity of sensor array variants was designed and evaluated by simulation using the so-called "Sinus Wave Approach" to design MS-WIM sites by calculating and evaluating maximum and mean values of measurement errors, deviation, distribution and envelope errors of equidistant and inhomogeneous layouts of WIM - sensor arrays depending on number of sensors used. To find out one or more good test sites, numerous possible equidistant sensor arrays with a maximum length of less than 24 meters and all kinds of vehicles types, which are represented by wave lengths of axles and body load oscillations, moving over these sensor arrays within the framework of the variability of the most important parameters were simulated. All variants of sensor arrays with different sensor distances from 0,25 to 7 meters were evaluated by calculating and comparing their mean values of maximum measurement errors depending on wave lengths from 2 to 20 meters using an increment of 0,25 meters. However, a mathematical model was needed for simulation of dynamic behaviour of moving vehicles. The results of the 1- sinusoidal wave approaches and the 2-sinusoidal wave model - were compared and tested in order to estimate the difference of measurement error.

The 2-sinusoidal wave model works on base of a superimposed load wave of vehicle weight and axle load, (see figure 4 and 5), The results of the simulation are:

- all maximum measurement errors – worst case;
- the mean value of maximum measurement error for each different sensor array;

- the mean value of maximum measurement error dependent on wave lengths for selected individual sensor arrays;
- the distributions of measurement error of individual sensor arrays and for each wave length;
- the distributions of the measurement error of a sensor array – over all wave lengths;
- the n % -quantiles of measurement errors and other interesting values.

The second simulator was developed to create individual vehicles crossing sensor arrays and to calculate dynamic axle loads and measurement errors of axle loads as well as vehicle weights and errors. These individual vehicles feature numerous specific properties such as speed, frequencies, weight, number of axles, distribution of weight and load on the axles. The interrelations between speed, wave length and dynamic load amplitude are variable too. (constant, digressive, progressive, proportional, or exponential functional interrelations are selectable).

The results of simulation were compared to the real-life data (sensor outputs) in order to validate and upgrade the basic approach by the use of an additional random procedure and others for improving the construction tool.

A specific mathematical optimisation model was developed to calculate optimum sensor distances for a given number of sensors, so that the deviation of mean values of the measurement errors over all wave lengths considered is at a minimum. The effect of changing the number of sensors used on the shape of an optimum WIM site was estimated and taken into account for selecting the best solution.

A graphic method for design of ‘good’ inhomogeneous sensor layouts on base of the maximum measurement errors depending on wave length was developed tested too.

An example of graphic construction of sensor arrays based on the use of the results of error simulation is shown in figure 6.

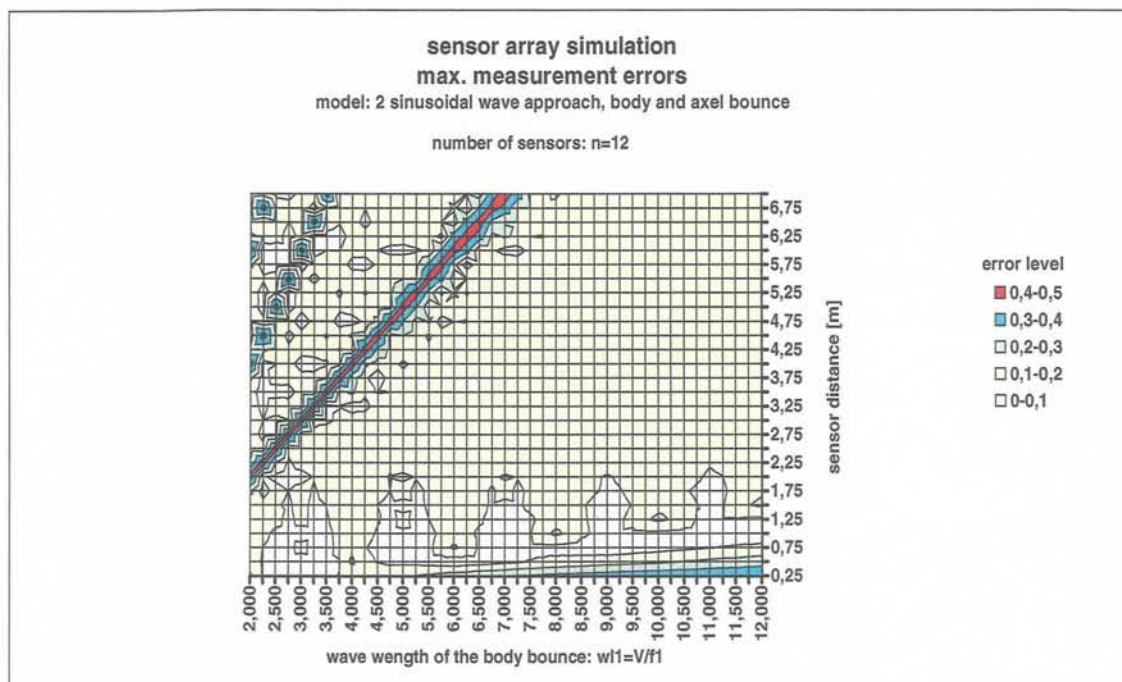


Figure 4 – Sensor array simulation, 2-sinusoidal wave approach

Figure 5 shows the optimum envelope measurement error depend on wave lengths calculated by the use of the numerical optimisation tool.

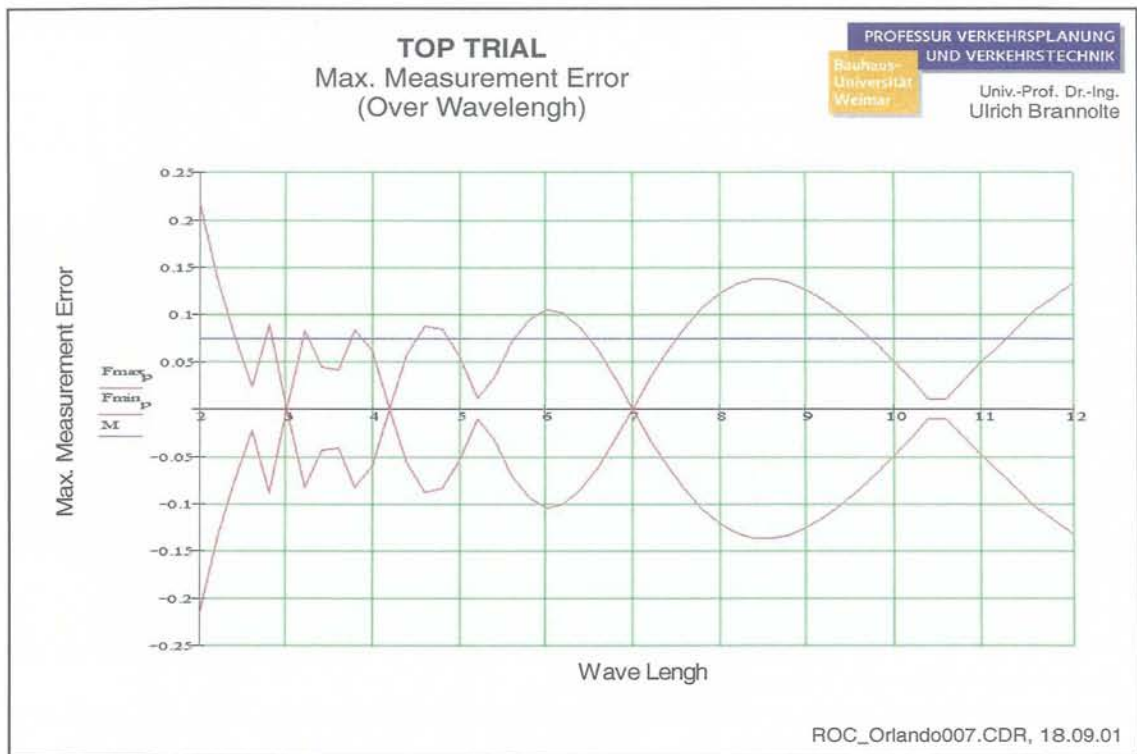


Figure 5 – Envelope measurement error diagram, optimum solution - 2 sinusoidal wave approach

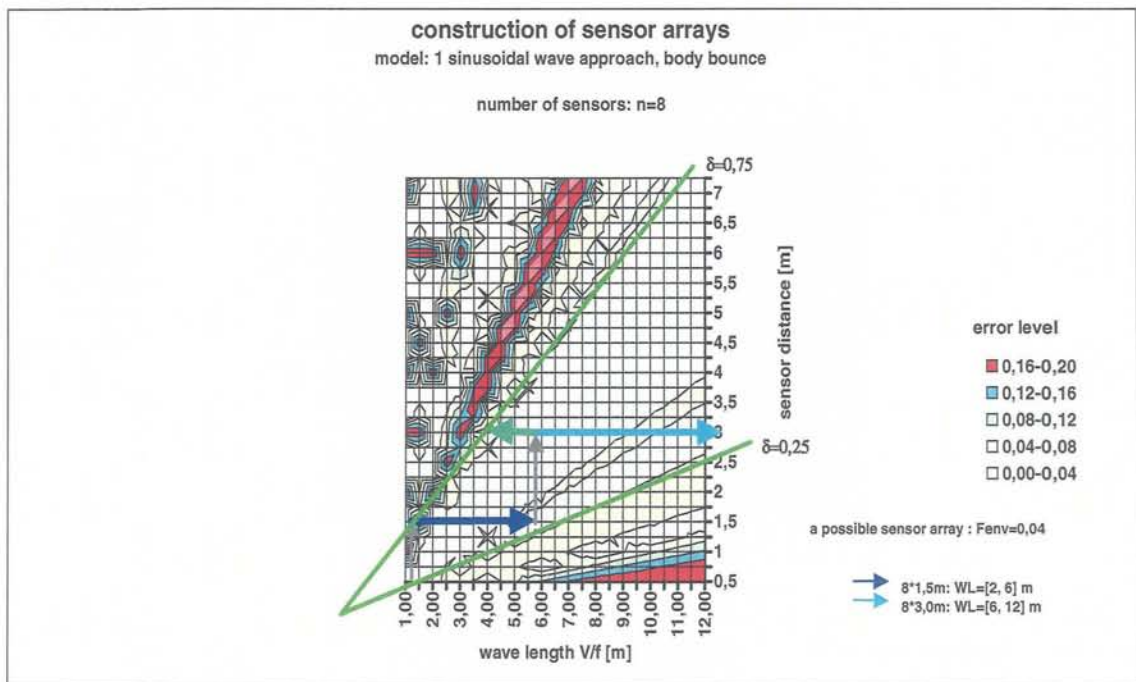


Figure 6 – graphic construction of a combined sensor array, - 1 sinusoidal wave approach

The maxima of all mean values of the measurement errors are calculated with regard to the variety of all possible phase cuts of the load oscillations and in evaluation of approx. 1.7 billion variants, a select few preferred variants were chosen, compared to each other and to the optimum sensor layout and proposed for the configuration of the equidistant MS WIM test site. The proposed sensor array with 12 sensors is an equidistant one with a sensor spaces of 2 meter.

The simulations of this sensor array have shown a good performance in range from 3 to 12 meters wave length. The measurement errors are relative high for wave lengths less then 3 meters.

### 3.2. Measurements

The dynamic measurement data were directly reported into the controlling container near the sensor array in order to be pre-checked and saved.

In the first two month 228 trucks with about 900 axles were analysed. The data quality of this two month was as like as expected and relative good static weights could be calculated. By the use of the averaging method an measurement error less than 5% of the static axle load with a probability of 83% was the result. Next two month the data deteriorated more and more. The probability of the 5% measurement error reduced to 80% and less.

Unfortunately the data quality reduced rapidly in the following month and the sensor array didn't work well since this time. So data of only 560 trucks could be used to develop effective algorithms for reducing measurement errors. The first measurement data will be saved under <http://www.toptrial.de/> soon.

### 3.3. Algorithms

A lot of algorithms for minimisation of measurement errors of dynamic weight measurements data of the multi-sensor WIM array were designed and tested by the use of. Different strategies were used to find out a precise static value for each axle load and vehicle weight. These strategies base on the averaging method, clustering method, tolerance interval method, Fourier-Transformation, curve fitting method, filtering methods and others. The results of the first two strategies are described in this article. A special extreme-value-removing (replacing)-method and a value-correcting-method have been used for calculation of errors of the articulated truck type '98' (two-axle tractor / three-axle trailer) and effected a significant improvement of the accuracy. The most effective methods have been combined and employed to improve measurement results, (see figure 7, 8 und 9).

These methods have been executed more times during the one-year TOP TRIL period but the impact of seasons and climatic conditions couldn't be calculated as the weighing technology used didn't work stabile over month .

The measurement accuracy is a product of construction and the use of the algorithms as well. The sinusoidal approach of construction of the sensor layout and the application of the developed algorithms effected an error of 5% with a probability of 87% only for axle 2 of all truck types.

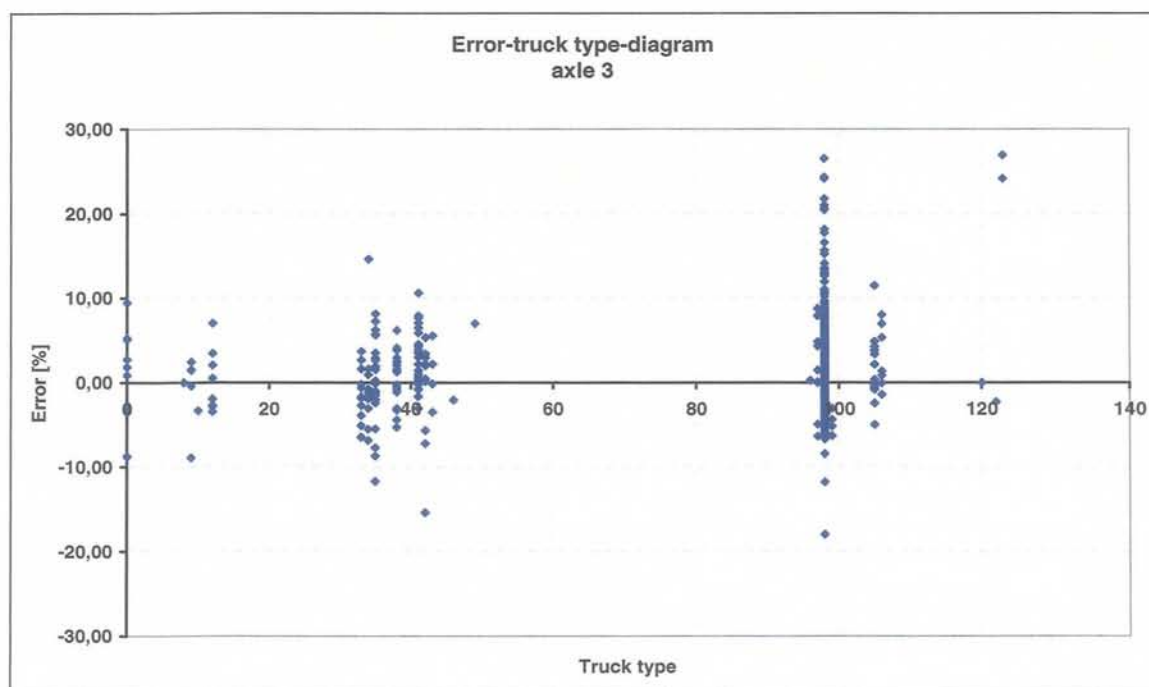


Figure 7 – Error-truck type-diagram, axle 3

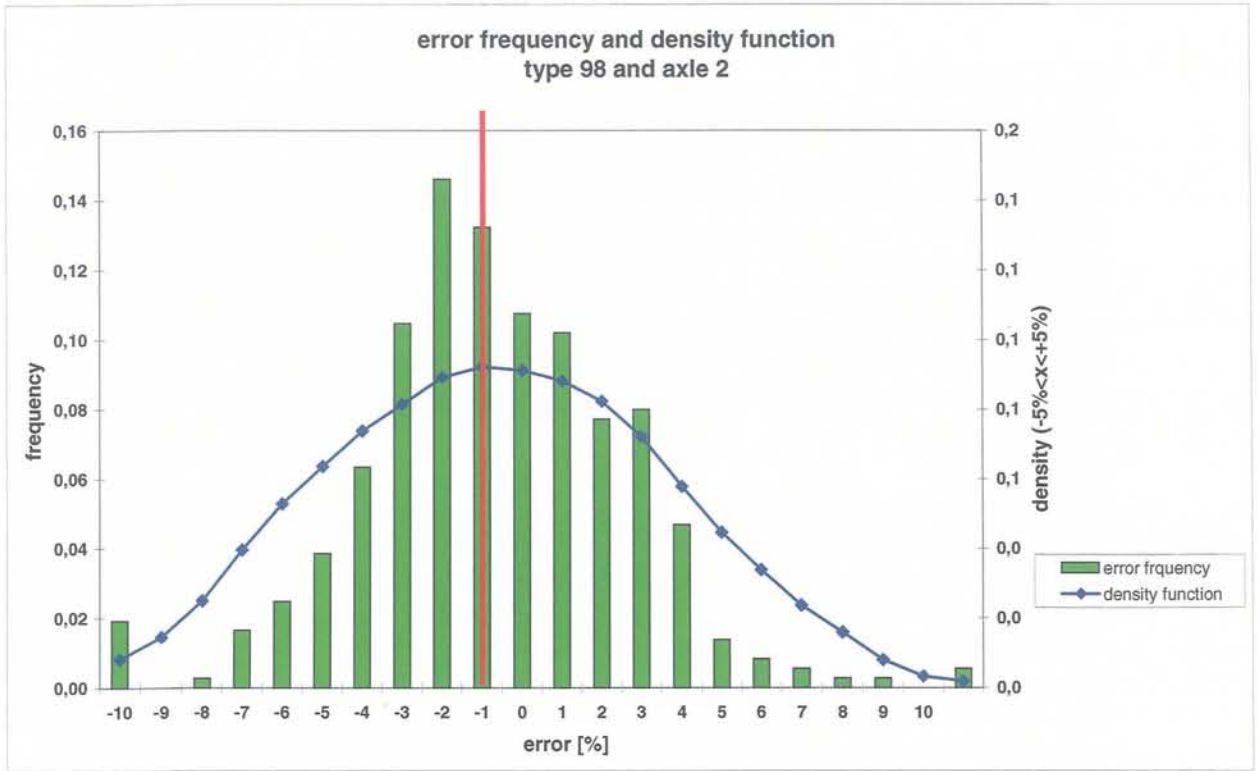


Figure 8 – Error frequency and density function, truck type 98 (two-axle tractor / three-axle trailer), axle 2

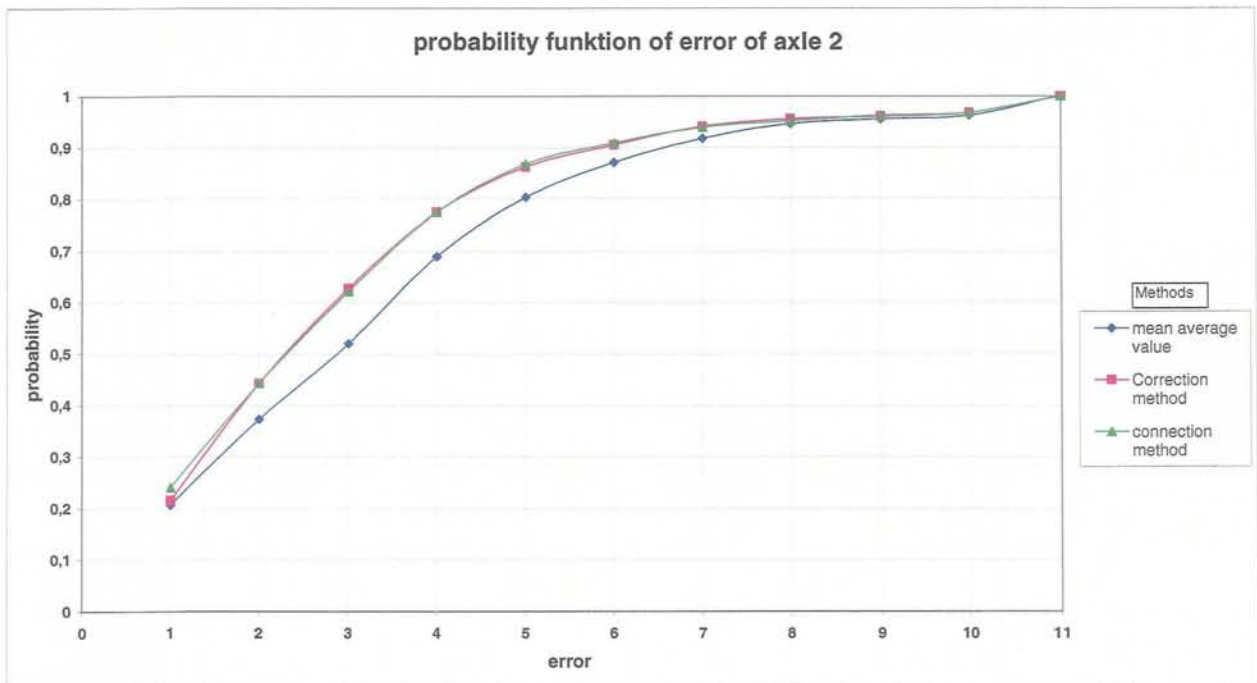


Figure 9 – probability function of axle 2 , all truck types

### 3. CONCLUIONS

In this project the WIM-sensor field was designed under the assumption of an uniform distribution of speeds and frequency of the traffic flow. Due to the lack of precise data of truck speed and load oscillation-frequency distribution the reality wasn't taken into account sufficiently. The feed back of the main characteristics, which should be worked out of the traffic flow, will lead to more suitable sensor layouts with lower measurement errors.

Other methods and algorithms such as curve fitting or Kahlman filtering method should be examined too. These methods were tested already but for single vehicles only, as a statistical validation needs much more programming work caused by connection of different software tools.

Further, researches are necessary to improve the measurement accuracy and probability in order to apply the automatic enforcement system.

The results of future measurements and analysis of the WIM test site, such as the empirical distributions of vehicle speed or the frequency of vehicle and axle load oscillations and others will substitute the model assumptions of the past phase and will have a decisive impact on the design of commercial WIM sites too.

#### **4. REFERENCES**

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