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ROAD TRAFFIC PARAMETERS MEASURING SYSTEM WITH VARIABLE STRUCTURE

Piotr Burnos, Janusz Gajda, Zbigniew Marszałek, Piotr Piwowar, Ryszard Sroka, Marek Stencel, Tadeusz Żegleń

Department of Instrumentation and Measurement, AGH University of Science and Technology, 30 Mickiewicza Street, Cracow 30059, Poland, Telephone: (+48) 12 617-39-72 (✉burnos@agh.edu.pl)

Abstract

Systems of road traffic parameters measurement play a key role in the process of road traffic control, its supervision as well as in gathering and processing information for statistical purposes. Expectations of users of such systems mainly concern automation and provision of measurement continuity, possibility of selection of the measured road traffic parameters and high accuracy along with reliability of obtained results. In order to meet the requirements set for such systems, at the Department of Instrumentation and Measurement of the AGH University of Science and Technology in Cracow a new prototype system of road traffic parameters measurement – Traffic-1 - has been constructed. The innovativeness of the solution is manifested in the structure of the system that can be modified by the user adequately to current measurement needs and in the used algorithms of signals processing. The work contains a brief description of the constructed system with particular focus on the used innovations that are the result of many years of research work of the designers.

Keywords: traffic parameters measurement, weigh-in-motion systems, vehicle classification.

1. Traffic-1 system structure

The Traffic-1 system (see Fig. 1) has been designed for a wide range of recipients with varied expectations concerning the selection of measured road traffic parameters [1]. The structure of the system is open and consists of a central unit and interchangeable modules for conditioning of signals from the measuring sensors. Modification of the structure and system function is limited to installation of a proper type of module in the system housing and connecting it with sensors. The system recognises the configuration and activates a proper parameter estimation algorithm. Nine interchangeable modules have been built, which means that the Traffic-1 system can operate as nine different systems cooperating with different types and number of sensors (mostly used on European roads).

Fig. 1. Traffic-1 system.

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The following configurations of measuring sensors [2] are possible:

A) Single inductive loop,
B) Two inductive loops array,
C) Two inductive loops array and axle detector,
D) Two inductive loops array and polymer load sensor,
E) Two inductive loops array and quartz load sensor,
F) Three inductive loops array,
G) Single inductive loop and 2 axle detectors,
H) Single inductive loop and 2 polymer load sensors,
I) Single inductive loop and 2 quartz load sensors.

Depending on the configuration, the system enables the measurement of the following parameters:

- T – time of arrival in the measurement zone,
- V – vehicle speed,
- L – vehicle length,
- N_{axle} – number of axles,
- L_{axle} – distance between axles,
- Trailer – trailer presence,
- Axle load – loads of individual axles,
- Total mass – total mass of the vehicle moving with a speed from 30 km/h up to 80 km/h (from 19 mph up to 50 mph),
- Cl. magnet – vehicle class based on magnetic profile,
- Cl. ALT – vehicle class based on the number of axles and the distance between them (different classification schemes are possible, e.g. Federal Highway Administration (FHWA) or ALTernative (ALT)).

Furthermore, the system enables specification of the following road traffic features [3]:

- k – traffic density,
- q – flow of vehicles,
- ρ – traffic lane occupancy,
- V_{mean} – mean speed.

Change of the type, number and configuration of the sensors not only facilitates measurement of different parameters of vehicles and road traffic, but also in many cases it influences the measurement accuracy. A comparison of the measured parameters with measurement accuracy for all configurations of measuring sensors [4] is presented in Table 1.

Table 1. Accuracy of measurement of road traffic parameters in the Traffic-1 system.

	T [s]	V [km/h]	L [m]	N_{axle}	L_{axle} [m]	Trailer	Axle load [N]	Total m. [kg]	Cl. mag.	Cl. ALT	k, q, r V_{mean}
A	0.01 s	6-23%	20%	–	–	x	–	–	x	–	x
B	0.01 s	1.5% *	2% *	–	–	x	–	–	x	–	x
C	0.01 s	1.5% *	2% *	–	2%	x	–	–	–	x	x
D	0.01 s	1.5% *	2% *	x	2%	x	20-30%	15-20%	–	x	x
E	0.01 s	1.5% *	2% *	x	2%	x	15-25%	15-20%	–	x	x
F	0.01 s	7.5%	8%	8%	10%	x	–	–	–	x	x
G	0.01 s	<1km/h	2% *	x	±2.5 cm	x	–	–	–	x	x
H	0.01 s	<1km/h	2% *	x	±2.5 cm	x	15-20 %	10-15%	–	x	x
I	0.01 s	<1km/h	2% *	x	±2.5 cm	x	10-15%	7-10%	–	x	x

NOTE: 1km/h = 0.62mph, 1cm = 0.39in, "*" - in the sense of standard deviation, "– "- unavailable, "x" – available.

The system has been equipped with an internal memory in which parameters of 150 thousand vehicles can be stored and an LCD touchscreen that enables control of system performance and real time visualisation of measurement results. A RS232 connection and a GSM modem have been chosen as the communication interface. They enable transmission of data to an external computer and wireless transmission of data to an ftp server. The use of GSM technology also gives the possibility of remote road traffic monitoring anytime from a computer with access to the Internet. The device has the capability of automatic detection of emergency conditions related with the installed sensors.

2. Innovations in the Traffic-1 system

The system utilises a range of innovative hardware and software solutions that increase the functionality and reliability of the equipment, and at the same time they contribute to its functional value. Such innovations include the algorithm of vehicle speed estimation in a system cooperating with a single inductive loop, detection of the number of axles of a vehicle on the basis of its magnetic profile, an algorithm of self-calibration and temperature correction of the results of weighing in the system cooperating with polymer load sensors and a new automatic method of vehicle classification ALT.

2.1. Algorithm of speed estimation in a system equipped with a single inductive loop

In classic ITS systems using axle detectors, vehicle speed measurement requires installing two sensors in the road pavement, at a specific distance, e.g. inductive loops, two polymer axle detectors or load sensors. The Traffic-1 system enables estimation of speed on the basis of a vehicle magnetic profile signal obtained from one inductive loop, which significantly lowers the cost of the whole system. The method was proposed in 1997 in [5] and it was also developed by other authors, e.g. [6]. In [7] the authors present an algorithm of speed estimation and vehicle-classification which is based on signals from a single inductive loop. The function of the algorithm used in the Traffic-1 system is illustrated by the relation (1) and Fig. 2.

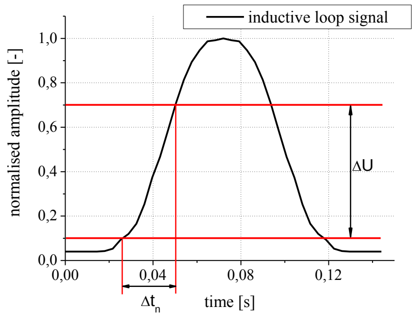

Fig. 2. Example of a signal from an inductive loop and estimation of the rise time with the method of two levels.

Vehicle speed is specified by the following algorithm:

$$V = a_1 \frac{\Delta U}{\Delta t_n} + b_1 , \tag{1}$$

where: V - vehicle speed estimation, Δt_n - rise time, ΔU - difference between predefined levels, a_1, b_1 - constant coefficients specified at the stage of calibration of the algorithm.

Exemplary results of speed measurement in a system with a single inductive loop in relation to a double sensor reference system are presented in Fig. 3.

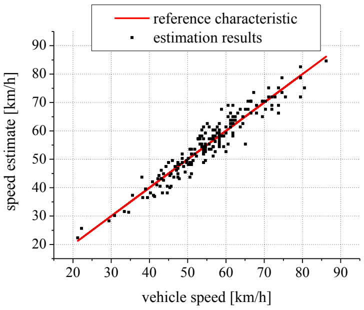

Fig. 3. Speed estimate of passenger vehicles specified according to algorithm (1) as a function of vehicle speed (NOTE: 1 km/h = 0.62 mph).

2.2. *Axle detection on the basis of the magnetic profile*

Vital vehicle parameters that are the subjects of the direct measurement are the number of axles and mutual distance between them. The standard includes measurement of these parameters in a system cooperating with piezoelectric, resistance, fibre optic or other axle detectors [2]. Rarely measurement systems are encountered using inductive loops for this purpose [8]. An important advantage of using loop sensors is significantly lower cost in comparison with other axle sensors. The Traffic-1 system uses two narrow sensors (10 cm – 3.93 in) and one wide-loop sensor with standard dimensions. Narrow loop sensors are used as axle detectors. Exemplary signals from a narrow loop sensor are presented in Fig. 4.

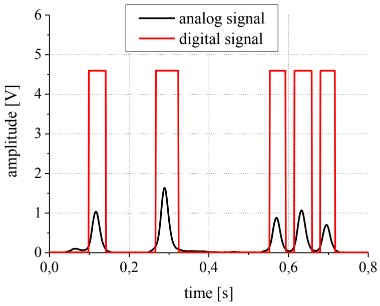

Fig. 4. Example of analog and digital signals from a conditioning system cooperating with a narrow inductive loop.

The number of axles of a vehicle and their mutual distances are the basis of automatic vehicle classification. Lorries are capable of lifting one or two axles. In such cases systems equipped with typical detectors give incorrect results of counting axles, which leads to erroneous classification of the vehicle. Systems equipped with inductive loop sensors do not have this fault and count correctly even those axles that are not in contact with the road pavement. The developed method is a subject in patent proceedings.

2.3. *Self-calibration and temperature correction of weighing results*

One of the major reasons of high uncertainty of weighing results in weigh-in-motion (WIM) systems with sensors installed in the road pavement is nonstationarity of the system. This phenomenon is caused by changes of pavement properties under the influence of temperature changes and it gains special significance in case of the use in the system of polymer load sensors [9]. It has been verified experimentally that changes of weighing results caused by the daily temperature cycle can reach 40% [10]. Traffic-1 system authors have developed two methods that enable the limitation of the influence of nonstationarity on the accuracy of the results: self-calibration and temperature correction of weighing results.

The concept of self-calibration consists in permanent estimation of the calibration coefficient *C* of the WIM system and modification of weighing results according to the currently specified estimation:

$$y_s(i)=\frac{1}{C}\cdot y(i)\,, \tag{2}$$

where: $y_s(i)$ – calibrated result of weighing the *i*-th vehicle i.e. estimation of total mass of the vehicle or static load of a selected axle, $y(i)$ – non-calibrated result of weighing the *i*-th vehicle i.e. result of processing of the load signal from the WIM system sensors.

A necessary condition that enables WIM system self-calibration is the occurrence of so-called reference vehicles in the stream of vehicles moving through the calibrated WIM site. These vehicles are regular road traffic participants and are distinguished by arrangement of three semi-trailer axles in mutual distances of 131 cm (51.57 in.), which significantly facilitates their identification, as well as small relative random variability of the first axle load (10%), the mean value of which is μ_0=61677 N (13860 lbf). It means that the load of this axle is stable, to a small degree it depends on the carried load, that is the total mass of the vehicle and can be used as a reference value during self-calibration of the system. Knowing the reference value μ_0 and having considered that the calibration coefficient should be specified in a constant manner, a recursive least-squares algorithm with modified exponential forgetting factor [10] has been used for its calculation. It has been verified experimentally that the use of the self-calibration method in a nonstationary system reduces the uncertainty of weighing results even five-fold.

The temperature correction method requires knowledge of the model of temperature characteristics of the WIM site and measurement of asphalt temperature in place of installation of sensors. Such a model can be specified using the results of weighing the first axle of reference vehicles. Fig. 5 presents experimentally-specified temperature characteristics within the range of -10 to 30°C (14 - 86°F). The data has been registered from November 2005 until January 2008 at the WIM site in Gardawice, south Poland [11]. At this time (with short pauses for system maintenance) over three million vehicles of different categories have been registered, including over 100 thousand reference vehicles. Each point in Fig. 5 (measurement data) is a mean value of weighing the first axle of thousands of reference vehicles at a selected asphalt temperature.

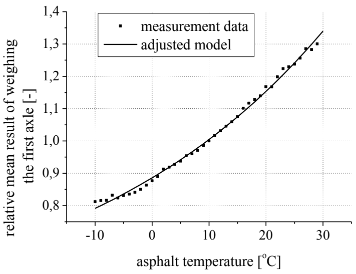

Fig. 5. Temperature characteristics of a WIM system within the range of -10 to 30 °C (14 - 86°F).

Within the range of temperatures from -10 to 30°C(14 - 86°F) the measuring data is well described by model (3), for which coefficients have been specified by the tuned model method (effective relative error of the model adjustment to the measurement data was 1%).

$$C_T(T_a)=k_T\cdot 10^{w_T\cdot T_a}+b_T\,, \tag{3}$$

where: T_a - asphalt temperature [°C], $k_T=0.4659$ - gain coefficient, w_T=0.0098 - curve inclination coefficient, b_T=0.4199 - offset.

Coefficients k_T, w_T, b_T are dependent on the type and composition of asphalt and they should be specified experimentally for each WIM site.

The nature of the temperature-correction method consists in using the model of temperature characteristics of the WIM station for calculating the value of C_T coefficient and in modifying the weighing results according to equation (4).

$$y_{ST}(i) = \frac{1}{C_0 \cdot C_T(T_a)} \cdot y(i), \tag{4}$$

where: C_0 - constant calibration coefficient specified, for example, by preliminarily weighed vehicle method in constant temperature T_a^0 *(11)*, $y_{ST}(i)$ - *i*-th result of weighing, including the temperature correction, i.e. total mass of a vehicle or static load of a selected axle.

The Traffic-1 system enables permanent measurements of asphalt temperature in place of installation of sensors, which implies the possibility of permanent correction of weighing results. Experiments have proved that the correction method makes possible even 4-fold reduction of uncertainty of weighing results in nonstationary systems.

2.4. Alternative automatic vehicle classification method

In the Traffic-1 system it is possible to select one of the implemented algorithms of automatic vehicle classification: Federal Highway Administration - FHWA or ALTernative - ALT [12]. In comparison with other methods, the ALT classification algorithm is distinguished by universality resulting from the open structure of the vehicle classification scheme as well as the use of fuzzy sets and data fusion in the identification algorithm. The classification is based on an elementary group of components (motorbike, car, delivery vehicle, lorry, tractor, trailer, semi-trailer, bus) out of which the user can build any number of vehicle categories. Due to that the method is characterized by high selectivity and flexibility because the number and type of vehicle categories can be adjusted to the nature of traffic in a given area. For example, 20 categories of vehicles most frequently occurring on Polish roads were created using an elementary group of components (8 categories of single vehicles, 6 categories of vehicle combination, 6 categories of articulated vehicles).

The functional basis of the identification algorithm is the measurement of parameters characterizing the vehicle, such as: number of axles, axle spacing and vehicle length that constitute a so-called vector of characteristic parameters. Decision on classification of a vehicle in a proper category is made by means of comparison of the characteristic vector value with the vector that is the model of this category. The models of vehicle categories in ALT classification (unlike classic solutions) have been built on the basis of fuzzy sets:

$$B = \{(\mu_B(x), x)\} \qquad \forall x \in X, \tag{5}$$

where: $X = \{x\}$ - is a certain wider set of values (in this case: distance between axles or vehicle length), $\mu_B : X \to [0,1]$ - is the membership function which to each element from space X assigns a degree of membership in the given fuzzy set: from non-membership ($\mu_B(x) = 0$) through partial membership ($0 < \mu_B(x) < 1$) to full membership ($\mu_B(x) = 1$).

For needs of the automatic vehicle classification algorithm, triangular (6a) and trapezoidal (6b) shapes of the membership function have been selected. Parameters of selected functions have been specified for each category of vehicles independently, on the basis of analysis of measurement data from the Polish Road Traffic Inspection Office, technical data of vehicles and the WIM system.

$$\mu_{Tri}(x)=\begin{cases} 1-\dfrac{|x-\mu|}{\alpha\cdot\sigma} & for \quad |x-\mu|<\alpha\cdot\sigma \\ 0 & for \quad |x-\mu|\geq\alpha\cdot\sigma \end{cases}, \qquad \mu_{Tra}(x)=\begin{cases} 0, & for \quad x\leq a \\ \dfrac{x-a}{b-a} & for \quad a\leq x\leq b \\ \dfrac{d-x}{d-c} & for \quad c\leq x\leq d \\ 0, & for \quad d\leq x \end{cases} \tag{6a, 6b}$$

Aside from the "membership — non-membership" alternative, characteristic for classical logic, the cases of partial membership also occur. An example of the triangle membership function of the fuzzy set "axle spacing" - is shown in Fig. 6.

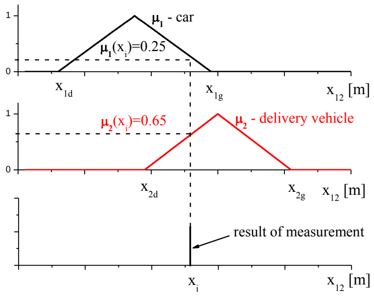

Fig. 6. An example illustrating the formulation of vehicle category models for triangle membership functions and the procedure in the event a new result of measuring the x_i is obtained.

The use of triangle membership functions eliminated the ambiguity characteristic to non-fuzzy sets. The membership function values μ_1 and μ_2 obtained in this example should be interpreted as the measure of membership of a vehicle with the axle spacing x_{12} in one of the two categories: a car or delivery vehicle. The value ($\mu_2(x_i)=0.65$) > ($\mu_1(x_i)=0.25$) indicates that the vehicle with measured axle spacing of x_i, "better" matches the category of delivery vehicles than that of cars. The presented considerations can be generalized for any *K* number of vehicle categories and *N* number of measured parameters. In this situation we obtain *N* values of adherence functions for each *K* category. The *N* values of the membership function obtained for a given category are combined by means of functions executing the data fusion. Two functions yielding the best results were found by testing:

$$f_1=\frac{1}{N}\sum_{i=1}^{N}\mu_i(x_i), \tag{7a}$$

$$f_2=\bigcap_{i=1}^{N}\mu_i(x_i)=\min(\mu_1,\mu_2,\ldots,\mu_N). \tag{7b}$$

The choice of the function depends on the number of vehicle axles. As the result of fusion we obtain one value (f_1 or f_2) for each category being considered. The largest value indicates the category to which the considered vehicle shall be assigned.

Experimental verification of the algorithm implemented in Traffic-1 system was conducted on the basis of 1097 recorded vehicles that had been assigned to adequate categories on the basis of visual specification. The result of the automatic classification was compared with the result of the visual specification of vehicle types, and the relation of correctly classified vehicles to the total number of test vehicles in a given category was assumed as a measure of effectiveness.

The effectiveness of classification of all the vehicles was 95%, while in case of lorries it was 100%. The overall effectiveness of ALT classification is 10% higher than that of FHWA. Furthermore, there were no unclassified vehicles. The obtained result confirms the correctness of the concept of using fuzzy logic and data fusion for automatic vehicle classification. Simplicity of the method (measuring the distance between axles and vehicle length), its universality and at the same time high effectiveness are definitely its advantages.

3. Conclusions

The constructed Traffic-1 measurement system is a universal tool for both long-term measurements of road traffic parameters as well as short-term measurements realised within the scope of research works. It can be easily moved between different measurement stations. The developed algorithms enable measuring a wide selection of vehicle parameters as well as traffic stream characteristics, at the same time minimizing the costs related with the used measurement sensors. The realized project is a summary of many years of scientific and engineering work of the team of constructors. The problem of road traffic parameter measurement has been present in research works realised at the Department of Instrumentation and Measurement at the AGH University of Science and Technology in Cracow for several years. Five research projects financed by the Ministry of Science and Higher Education, including one development project, have been realized in this period. Several measurement systems with different degrees of complexity, cooperating with different number and types of measuring sensors for different parameters have been designed and built.

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