VEHICLES' WEIGHT METHOD UNDER OPERATION

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Abstract: The article contains an example detailing the application and analysis of the accuracy of the method called continuous dynamic vehicle weighing during travel, using the telematic system. A model was built using the input data obtained through laboratory experiments on a running vehicle. This model was then applied to study the effects of error probability for the measured input data on the resulting expected accuracy of vehicle weight measuring in a normal running regime. Based on this point, hereby presented is a proposal of selected measured variables of great importance, and a proposal for the computation relationship of the used variables. By statistically processing a set of measured data taken during one vehicle travel, it is possible to attain –10.7% extreme relative error of the given method for the dynamic determination of vehicle weight.

Key words: *Dynamic weighing of vehicles, telematic system, torque, forward thrust on the wheels, running resistance, road gradient*

Received: March 3, 2011
Revised and accepted: April 8, 2011

1. Introduction

Overloading of transport is causing enormous problems in road transportation. It is not easy to manage and maneuver an overloaded vehicle. An overloaded vehicle can became laterally unstable at relatively low speeds and, therefore, uncontrollable with all consequences for road safety. Such vehicles are, therefore, a danger to road traffic. In addition, overloaded vehicles wear away the roads due to progressive pressure on the road surface. This leads to an unproportional increase in the road rehabilitation costs.

This paper presents a technical elaboration of conditions and the relations needed for a continuous weighing of vehicle unit during travel [4]. The principle of application is the following quote: "the motive-derived dynamic data is recorded during travel, therewith as a component, together with all the external recorded forces and other factors acting on the vehicle, are assessed together with the oncoming corrections of external or implemented data in the onboard computer

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that is mounted in the vehicle according to law of inertia and other laws of nature, whereas the obtained data of the vehicle is input into the onboard computer telematically and/or supervisory or by means of a master system and/or digital speed recording indicator and/or into the system of electronic toll and/or into the management of transport telematic system etc. for further decision making and/or for the optimizing of operation driving parameters of the vehicle unit", end of quote.

2. An Example of Experimental Weighing

The readings and calculations in this article are based on the passenger vehicle with following specifications: service weight 840 kg, payload 450 kg, standard tires 165/70 R 13. The authors had all the essential data that was needed for continuous weighing of the vehicle during travel. The data were acquired as part of a broad collection of measured data meant for a wide range of special-purpose experiments. This example is being presented as a model that is based on the application of the respective laws of nature, which are, in principle, applicable to many types of road vehicles of various design principles and information circuits [7].

2.1 The basic data of measured vehicle

The torque characteristics were taken from the homologation report and purpose report that had been modified through the technical inspection of the vehicle.

$M(n)$ The characteristics show the continuous dependence of engine effective torque M [N.m] on engine speed [revs per min].

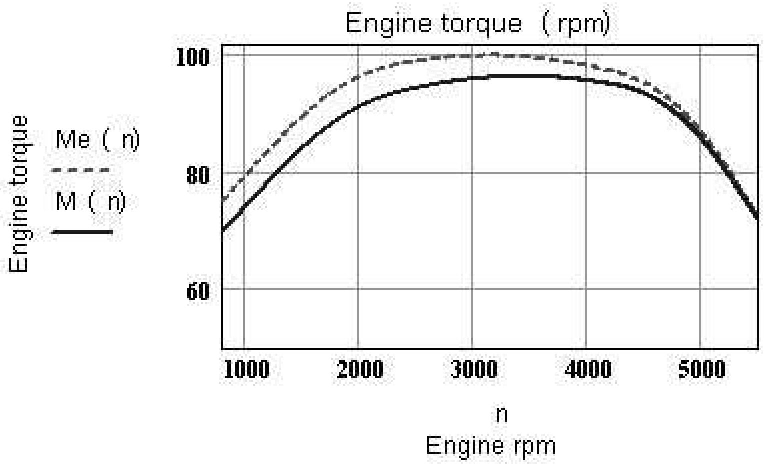

Fig. 1 *External characteristics showing the dependence of engine effective torque, (y-axis), on engine speed, (x-axis). The standard sound engine is represented by the dotted curve $M'(n)$. For the measured worn engine, a full curve is used $M(n)$.*

The given characteristic $M(n)$ signifies an extraordinary data input into the calculations thereinafter, because it is the only predefined component. Given its size, it compensates all the passive resistances, mainly the resistance that is dependent on the weight under study. Fig. 1 shows the so-called external torque characteristics at full throttle.

In principle, once we take into account the relationships of other independent variables, namely the position of the accelerator pedal, it is possible to arrive at a continuous definition of the corresponding trends in torque characteristics and realize a random measuring of system to determine prevailing fuel supply. In comparison to the given external characteristics, for any type of torque characteristics the value of its torque in relation to engine speed in all cases could be only lower; from the analysis given below we can deduce that these less used values have always a negative impact in the form of poor measuring accuracy. It is possible to state that the resulting errors of dynamic measuring of vehicle weight according to the above cited registered invention, if carried out at half throttle, there is roughly a twofold increase in errors, in comparison to the full throttle case.

For rational use of the given method, only a suitable choice and processing of random vehicle regimes can be recommended. This should be done under full throttle. This full throttle can even be short term, having duration of few seconds required for stable transition feature of fuel supply. The next analysis of the given problematic, therefore, results from given advantageous prerequisite. If this prerequisite is not respected, it will lead to a decrease in the input torque characteristic that will unproportionally increase the resulting test error. This is also linked to the recommendations in the invention report that says that tests should not be carried out in first gear because in that case there is a higher probability that full fuel supply causes big high slip, which is unacceptable for measurement reasons.

The other problem that is connected to the given torque characteristic $M(n)$ is the precision of its update within the framework of the supposed modifications of the measuring procedures during technical inspections of the vehicle. In Fig. 1, the torque characteristics were updated just before the experiment. The car had undergone normal wear at 150 000 km mileage. The effective torque in this case decreased mainly at low engine speed. This was a manifestation of a partial loss in compression pressure resulting from the wear of pistons and cylinders. This phenomenon that is irreversible and mechanically nonadjustable must be registered during technical inspections and all the affected characteristics should be entered into the updated engine database.

From the viewpoint of degenerative changes in the mechanical components of any type of vehicle that are related to use, the given changes in the characteristics $M(m)$ will always be negative. In case they are updated at technical inspection intervals of an average 100 000 km mileage, we can, based on the earlier experiments recorded by the authors, suppose that the relative minus diversion will not be greater than –3%. For the rest of torque changes, which are random, and those that can be corrected through maintenance, it is imperatively in the interest of the user that they be corrected. This is due to the fact that any minus or plus diversions from the standards given by the manufacturer will almost always lead to worsening economic, dynamic, driving and safety conditions of the vehicle. In spite of this it is necessary to suppose that as a result of the given random phenomena, the characteristic $M(n)$ can decrease roughly by another –7%, thus by a total of about –10% (see below).

For the given test requirements, the following data must be known for each type of vehicle. The concrete data have been taken from the test measurements carried out on a passenger car.

Im* = *0.142 *[kg.m^2] it is the moment of inertia of a revolving component of an engine connected to the clutch, scaled on to the crankshaft.*

Is* = *0.002 *[kg.m^2] it is the clutch dragged moment of inertia, including the whole transmission system. In the case of the method under investigation,* ***Is*** *does not enter the computations as an independent variable, but as a part of* ***Im.***

Ia* = *0.901 *and* ***Ib 0.901*** *[kg.m^2] gives the total moment of inertia of all driving wheels (a) and all driven wheels (a), including the complete system auxiliaries and their axis reduction.*

ka* = *0.118 *[N/kg] gives the coefficient for all the constant components of rolling resistance for a standard surface.*

kb* = *0.003 *[N.s/kg.m] it is the coefficient of linear dependence between the rolling resistance and vehicle speed on standard surface.*

SP* = *2.5 *[m^2] is the front surface area of the vehicle car body.*

cw* = *0.32 *is the aerodynamic resistance of the vehicle.*

ρ = ***1.202*** *[kg/m^3] is the air density. The value is updated from the database for above sea level height of a given section of the road.*

$\boldsymbol{ip_s}$= ***4.935*** *is the total gear ratio between the crankshaft and the driving wheels in gear* ***s = 3.***

up* = *0.96 *is the mechanical efficiency for energy transmission from the crankshaft to the driving wheels at a given nominal load and at standard road quality and running temperature of the oil.*

2.2 Data measured during vehicle travel

As an example we have selected two readings on passenger car. During the first test, denoted by the index 1, the vehicle was loaded with three persons; it had the standard fittings including fuel in the tank. In the second test, a person weighing 106 kg left the vehicle but the rest of the conditions remained the same; this test is denoted with index 2. In the two given evaluations, I =1 and I =2, the following readings were taken:

$\boldsymbol{Mv_1}$= ***1209*** *and* $\boldsymbol{mv_2}$= ***1103*** *[kg] is the static taken weight of the vehicle during 1 and 2 tests.*

$\boldsymbol{n_1}$= ***2357*** *and* $\boldsymbol{n_2}$= ***2501*** *[min^{-1}] the frequency of rotations for the crankshaft during 1 and 2 tests.*

Ra* = *0.274 *[m] is the updated rolling radius of the vehicle drive wheels during travel.*

$\boldsymbol{v}_1$ **= *48.78*** *and* $\boldsymbol{v}_2$**= *51.79*** *[km.h*$^{-1}$*] is the linear speed of the vehicle during test 1 and 2, which was determined from the frequency of drive wheel rotations (they can also be measured telematically).*

$\boldsymbol{a}_1$ **= *0.959*** *and* $\boldsymbol{a}_2$**= *1.065*** *[m.s*$^{-2}$*] linear acceleration of the vehicle during test 1 and test 2, which were determined through the derivation of speed* $v_1 = v_2$ *against time. (It can also be measured by using the gravity sensor.)*

$\boldsymbol{vx}_1$**= *1.8*** *and* $\boldsymbol{vx}_2$**= *-2.5*** *[km.h*$^{-1}$*] it is perpendicular to the vector projection of speed along the longitudinal plane of the vehicle (it is measured using the anemometer and it is taken as the mean value for a given section of the road). The value is positive in the direction of the vehicle and it is negative in the opposite direction.*

α_1 **= *-1.1*** *and* α_2**= *-1.1*** *[%] it is the elevation of a given section of the road expressed in %, i.e. 100.tangent.*α. *The value is positive uphill and negative downhill. (Measured using the inclinometer and taken as a mean value of the road section.)*

Fig. 2 to Fig. 5 give the measured data and the primary data computation of the given case.

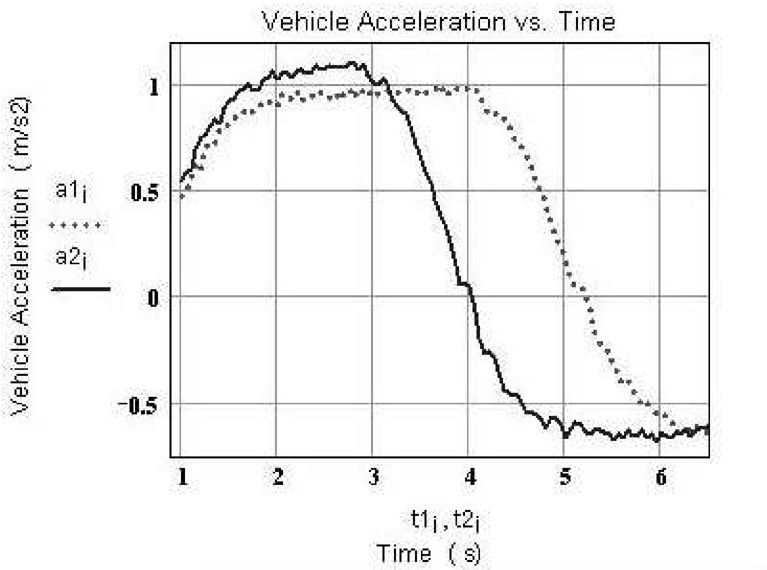

Fig. 2 *Linear acceleration* a_1 *and* a_2*[m.s*$^{-2}$*] of the vehicle during the first measurement (lower value) and second measurement (higher value) in relation to time* t_1 *and* t_2*[s].*

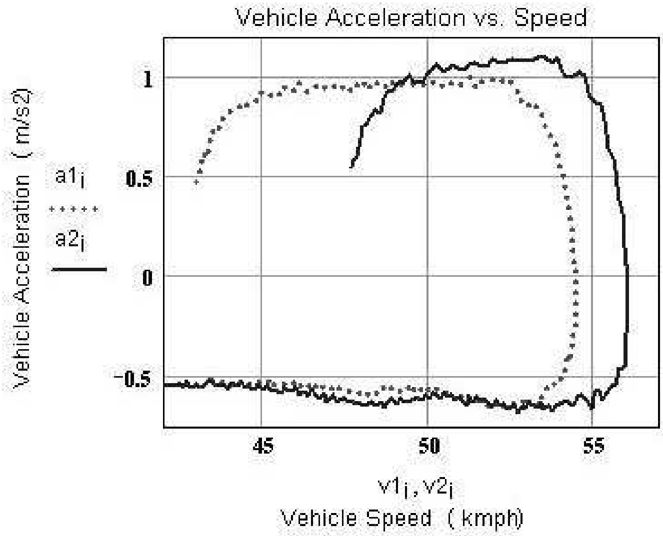

Fig. 3 *Linear acceleration $a_1[m.s^{-2}]$ of the vehicle during the first measurement and second measurement in relation to vehicle speed $\boldsymbol{v}_1$ and $\boldsymbol{v}_2[km.h^{-1}]$.*

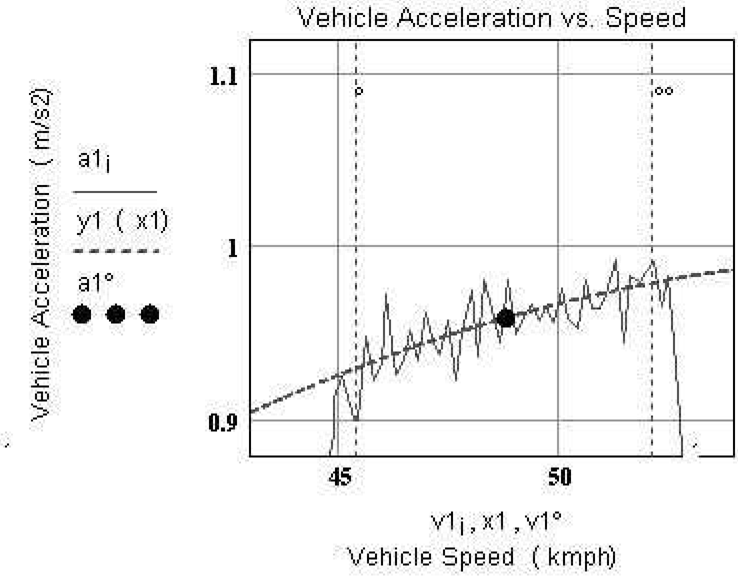

Fig. 4 *Details of linear acceleration $a_1[m.s^{-2}]$ of the vehicle interlarded with a regressive curve $\boldsymbol{y}_1$ and its mean value $\boldsymbol{a}_1$ for a measured road section.*

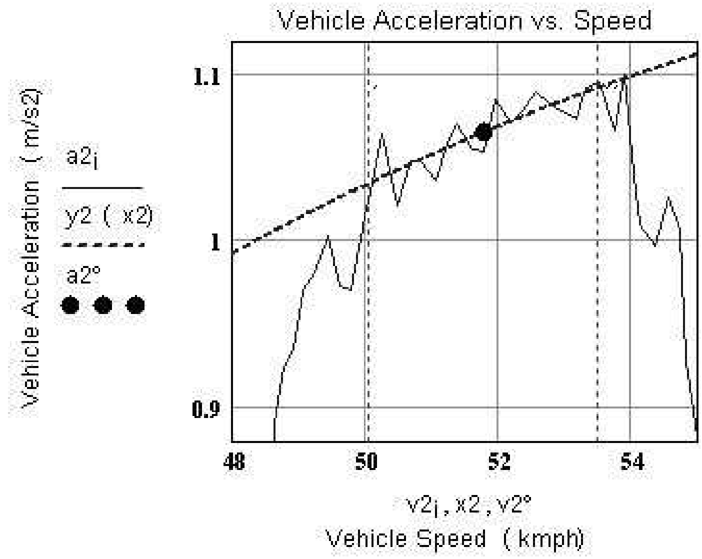

Fig. 5 *Details of linear acceleration* $\boldsymbol{a}_2$*[m.s^{-2}] of the vehicle interlarded with a regressive curve* $\boldsymbol{y}_2$ *and its mean value* $\boldsymbol{a}_2$ *for a measured road section.*

2.3 Computing the dynamic measuring of vehicle weight

The methodology used in this approach is hard and exact. The results from soft methods can lead to more general conclusions and sensitivity analysis [5], [6]. Nevertheless, the purpose of the method requires exact evaluation of singular cases.

In random regime, all the forces acting on the circumference of the vehicle wheel are in equilibrium. Under conditions where all the insignificant components of the given forces, e.g. the temperature effect of engine and transmission oil, pressure effect, temperature effect, air humidity effect, the effect of road surface adhesion properties etc., are neglected, we can derive the following relation (8) for computing the dynamic weight of the vehicle.

There are following partial components of the formula (8):

$$Fh_i := \frac{ip \cdot up}{Ra} \cdot M(n_i) \qquad [\mathbf{N}] \tag{1}$$

Fh_i **[N]** is the force component, acting on the vehicle driven wheels in sequence i of the measured time, given by the torque of the engine M [N.m] and expressed as a dependent of engine rotations n_i[min^{-1}], total gear ratio ip, mechanical efficiency up and rotation radius Ra [m] of the driving wheels.

$$Fr_i := -a_i \cdot \left(\frac{ip^2 \cdot Im}{up \cdot Ra^2} + \frac{Ia + Ib}{Ra^2} \right) \qquad [\mathbf{N}] \tag{2}$$

Fr_i **[N]** is the force component acting on driving wheels, necessary for angle acceleration of rotating masses of the vehicle, expressed as a dependent of acceleration

a_i [m.s^{-2}] of the vehicle in its longitudinal axis, total gear ratio ip, moment of inertia Im [kg.m^2] at rotating parts of the engine, moment of inertia at driving Ia [kg.m^2] and driven Ib [kg.m^2] wheels of the vehicle, mechanical efficiency up and radius of rotation Ra [m] of the driving wheel.

$$Fv_i := -\frac{0.5 \cdot \rho \cdot cw \cdot SP}{3.6^2} \cdot (v_i - vx_i)^2 \qquad [\mathbf{N}] \tag{3}$$

Fv_i [**N**] is the force component acting on driving wheels, necessary to cope with the resistance of the air, acting on the car body and dependent on the common air density ρ kg/m^3], and resistance coefficient cw, frontal area SP [m^2], speed of the vehicle v [km.h^{-1}] and speed of the car vx [km.h^{-1}] in its axis.

$$Fa_i := -m_i \cdot a_i \qquad [\mathbf{N}] \tag{4}$$

Fa_i [**N**] is the force component on the driven wheel, necessary to actuate the acceleration a_i [m.s^{-2}] in the axis of the vehicle, given its total weight m_i [kg].

$$Fb_i := -m_i \cdot \left(ka + \frac{v_i}{3.6} \cdot kb\right) \qquad [\mathbf{N}] \tag{5}$$

Fb_i [**N**] is the force on the driving wheels necessary to cope with the rolling resistance, composed by the coefficient ka [N/kg] constant and coefficient kb [N.s/kg.m] of the linear dependency on total vehicle weight m_i [kg].

$$Fc_i := -m_i \cdot 9.807 \cdot sin\left(atan\left(\frac{\alpha_i}{100}\right)\right) \qquad [\mathbf{N}] \tag{6}$$

Fc_i is the force component on driving wheels, based on the road angle α_i[%], which is expressed as tangents of the angle $\alpha_i/100$. The angle in radial measure is arcus tangens ($\alpha_i/100$) and the value of its sinus corresponds to the force necessary to eliminate the road angle at the given gravitation constant and total weight of the vehicle m_i [kg].

The sum of the above mentioned forces equals to zero

$$Fh_i + Fr_i + Fv_i + Fa_i + Fb_i + Fc_i := 0 \qquad [\mathbf{N}] \tag{7}$$

The total of the dynamically set weight of the vehicle equals to:

$$m_i := \frac{\frac{ip \cdot up}{Ra} \cdot M(n_i) - a_i \cdot \left(\frac{ip^2 \cdot Im}{up \cdot Ra^2} + \frac{Ia+Ib}{Ra^2}\right) - \frac{0.5 \cdot \rho \cdot cw \cdot SP}{3.6^2} \cdot (v_i - vx_i)^2}{a_i + \left(ka + \frac{v_i}{3.6} \cdot kb\right) + 9.807 \cdot sin\left(atan\left(\frac{\alpha_i}{100}\right)\right)} \qquad [\mathbf{N}] \tag{8}$$

Each given input value was repeatedly measured with a higher degree of statistical compensation for all random errors and precisely rounded off to one decimal place. As a result, upon substitution for the values in relation 2, we get relatively accurate results. The relative extreme error for dynamic determination of the vehicle is, in this case, roughly equal to 0.6%. It must be mentioned here that the torque $M(n)$ was updated just before the experiment. This was done with the same precision as for quasi-static measuring 0.5%. This will evidently not be possible to realize under normal operational circumstances.

3. Expected Precision of Dynamic Measuring of Vehicle Weight During Normal Operation

The repeatability of tens or hundreds of measurements has been proved. When running the verified model, for many of the input variables the same values or values of higher precision are obtained in repeated measurements – in some cases the results are better than the ones given in the example. For the torque characteristics $M(m)$, statistical compensation does not help. From the computation point of view, the torque characteristic has an extraordinary importance. The torque characteristic is not only burdened by random error, but also by the systematic error. The systematic error is a result of a gradual increase in different engine faults and failures.

Based on the present measured data and experience, the authors suppose that the diversions of characteristics $M(n)$ from the normal that are encountered in engine operations will, as a rule, be negative. They will not be more than 10% of the standard value of the new run-in engine. The given limit of 10% is so big and in general it would cause intolerably great losses in power with its corresponding vehicle utilization; this would also cause an increase in fuel consumption that would be to the dislike of the user.

The given hypothesis is documented in the Tab. I. The results of the experiments have been used to show that according to [1], relative errors in dynamic measurements of vehicle weight can be expected to reach roughly 10%. This means that in comparison to the actual readings taken in operations the values will generally be higher, maximum 10.7%.

Object under experiment	Weighing the determined weight [kg]	Dynamic measured weight[kg](*)	Absolute error of dynamic measurement [kg] (*)	Relative error of dynamic measurement [%] (*)
Vehicle at 1^{st} reading	1209	1202.9 (1337)	-6.1 (128)	-0.51 (**10.6**)
Surmounting person	106	105.9 (116)	-0.1 (10)	-0.1 (**9.5**)
Vehicle at 2^{nd} reading	1103	1096.9 (1221)	-6.1 (118)	-0.56 (**10.7**)

(*) The values indicated outside the brackets were measured in the given experiments where the torque characteristics $M(n)$ were updated just before the experiments. The probable errors are shown in brackets. These can be expected due to the fact that the torque characteristics can decrease by 10% during normal operations, and such situations cannot be updated.

Tab. I *The resulting error of dynamic measuring of vehicle weight and surmounting person.*

4. Recommendations for Application

If we take into consideration the fact that the operation diversions on the torque characteristic $M(n)$ will only be negative, and that its statistical distribution will be close to Gaussian curve and that the diversion error will be the limit value

$3\sigma_1 = 10.7\%$ in the first two years from the first update of $M(n)$, the following realization possibilities are on offer:

1. During regular technical inspections the torque characteristic $M(n)$ should be updated after every two years to a precision of $\sigma_2 = 0.5\%$ of the mean error. This is technically possible.

2. The updated torque characteristics $M(n)$ will deliberately be reduced by $\sigma_1 + \sigma_2 = 3.6\%$. This will ensure that 67.7% of the results obtained from vehicle weighing will be lower than in reality, and at most 3.6% in favor of the user.

3. The remaining 31.3% of the results will be greater than in reality and at most 10.7% to the disadvantage of the end user. Since any drop in $M(n)$ characteristics has an unfavorable effect on fuel consumption and emission production, this measure seems to be an acceptable stimulus for maintaining vehicles in good technical conditions.

We should further take into consideration the necessity to thoroughly respect the recommended conditions for these experiments, as stipulated in PV 2003-3337. Mainly, these conditions do not recommend taking measurements at acceleration which are less than zero, at breaking, in first gear or in neutral, at higher wheel slips, while negotiating corners and bends, under snow cover above specified limits, at speeds and wind gusts over specified limits, under heavy rains and snow and under glaze conditions. All these given circumstances could cause further systematic errors in readings, which the given analysis does not define.

Acknowledgement

This paper is supported by:

1. Ministry of Transport of the Czech Republic (project No. CG912-058-520) Methodology of quantification and assessment of transport's environmental and safety impacts.

2. Ministry of Education, Youth and Sports of the Czech Republic, action EU COST 356 "Towards the definition of a measurable environmentally sustainable transport" integrated project COST 356, No. OC 193. "The assessment methods and multidisciplinary evaluation of transport impacts on the sustainable environment".

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