IN-VEHICLE WEIGHT-IN-MOTION MEASUREMENT

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ABSTRACT

This paper examines results of the current research and development in the area of weigh-in-motion systems using the processing of in-vehicle data together with other measured data like acceleration, weather conditions, etc. The described data processing results in the determination of vehicle weight that can be used for weigh-in-motion applications (continuous dynamic weighing of overloaded vehicles on roads and highways during travel, evaluation of public transport line occupancy, etc.).

This paper presents the technical elaboration of conditions and equations needed for continuous weighing of vehicle units during travel. The telematic system contained in the patent application CZ PV 2003-3337 is used. The principle of the patent application can be summarized as follows: "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 that is mounted in the vehicle according to law of inertia and other physical laws, 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 optimization of operation driving parameters of the vehicle unit."

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1 INTRODUCTION

Overloading of vehicles is causing substantial problems in road transportation. The maneuverability of overloaded vehicles is difficult and such vehicles are therefore dangerous to road traffic. Such vehicles are therefore a danger to road traffic. In addition, the intensity of wear of roads increases progressively with the vehicle load which results in enormous costs of road network maintenance.

This paper presents the technical elaboration of conditions and equations needed for continuous weighing of vehicle units during travel. The telematic system contained in the patent application [1] is used. The principle of the patent application can be summarized as follows: “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 that is mounted in the vehicle according to law of inertia and other physical laws, 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 optimization of operation driving parameters of the vehicle unit.”

2 AN EXAMPLE OF EXPERIMENTAL WEIGHING

The readings and calculations in this article are based on the passenger vehicle – SKODA FAVORIT 136 L. Specifications: - engine type 781.136, - service weight 840 kg, - payload 450 kg, - tires 165/70 R 13 with OR 37 design. The authors had all the essential data needed for continuous weighing of the vehicle during travel. The data was 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 physics, which are in principle applicable to all types of road vehicles.

2.1 The basic specification of the measured vehicle

The torque characteristics were taken from the homologation report and for this purpose modified technical inspection of the vehicle.

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

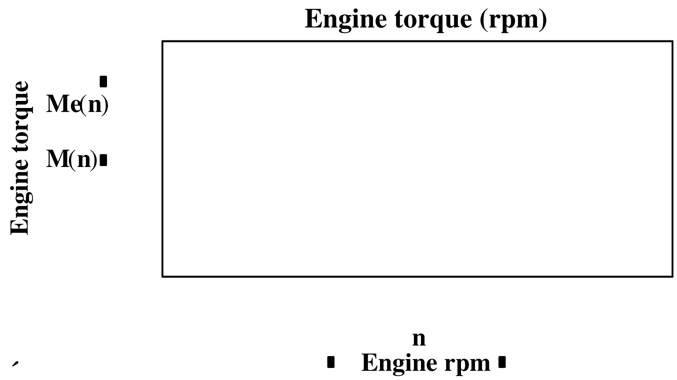

Figure 1. External characteristics showing the dependence of engine effective torque (y-axis) on engine speed (x-axis). The standard perfect engine is represented by the dotted line M’ (n), the measured worn engine is represented by the solid line M (n).

The given characteristic M (n) represents a particularly important data input into the calculations presented in this paper. It is the only active predefined component, which, given its size, is able to compensate for all the passive resistances, mainly those resistances dependent on the measured weight. Figure 1 shows the so-called external torque characteristic 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 determine the corresponding changes in torque characteristics and develop a system of measurement for any level of fuel supply which can occur in operation of the vehicle. 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 can only be lower; from the analysis given below we can deduce that these lower values have always a negative impact in the form of worse measurement accuracy. It can be stated that the resulting errors of dynamic measuring of vehicle weight (according to the above-cited patent application) can roughly double while measuring at half throttle in comparison to the full throttle case.

For rational application of the method it should be recommended to select and process only those suitable random vehicle regimes under full throttle. This full throttle state can even be very short – duration of only few seconds is needed for stabilization of fuel supply transition effects. The following study of the given problem is therefore based on the described advantageous prerequisite. A failure to meet this prerequisite will result in increase of the measurement error due to decreased input torque characteristic. This is also related to the logical recommendation in the patent application stating that measurements should not be carried out when the first speed gear is engaged because full fuel supply may cause unacceptable wheel spin distorting the measured values.

Another problem related to the given torque characteristic M (n) is the accuracy of updating the characteristic within the framework of the supposed modifications of measuring procedures for technical inspections of vehicles. The torque characteristic of an engine with usual wear at vehicle mileage of 150.000 km (depicted in Figure 1) was updated shortly before the experiment. The effective torque in this case is decreased mainly in the area of low engine speed due to partial loss of compression pressures caused by mechanical wear of pistons and cylinders. Such irreversible and mechanically not removable phenomena must be found during technical inspections and the affected characteristic should be updated in the engine database.

Considering the operation-caused degradation of mechanical components of common engine types, the mentioned shift of the M (n) characteristic will always be negative. In case the intervals of technical inspections are shorter than mileage 100 000 km, we can assume (basing on the earlier experiments carried out by the authors) that the relative difference will not exceed - 3 %. It can be expected that other (random and repairable) changes of torque characteristic will be repaired by the users as soon as possible, because these changes result in worse economy of vehicle operation and deteriorated dynamic and safety characteristics of the vehicle. However, it should be assumed that due to these random events the characteristic M (n) can be decreased roughly by 10 % in total (see below).

For the purposes of the measurement, the following data must be known or determined for each type of vehicle. The listed values are taken from the presented example of measurement on FAVORIT 136 L:

Im = 0.142 [kg.m^2] is the moment of inertia of revolving parts of the engine including the connected parts of clutch, scaled on to the crankshaft.

Is = 0.002 [kg.m^2] is the moment of inertia of the dragged parts of clutch, including the connected parts of transmission system. **Is** is not a separate input to the calculation, but is included in **Im.**

Ia = 0.901 and **Ib 0.901** [kg.m^2] are the total moments of inertia of all driving (a) and all driven wheels (b), including the connected parts of transmissions and brakes, scaled on to wheel axes.

ka = 0.118 [N/kg] is the coefficient of the constant component of rolling resistance of vehicle wheels on standard road surface.

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

SP = 2.5 [m^2] is the front surface of the vehicle 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 a database for the actual elevation of the given section of the road.

ip_s = 4.935 is the total gear ratio between crankshaft and driving wheels for speed gear **s = 3.**

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

Note: In the presented method of dynamic measurement of weight-in-motion, the actual engine torque is not measured by means of dynamometer, but using a special quasi-static measurement. The basis of the quasi-static method is that the engine is shortly loaded by common external operational load. Thus the engine working regime gets stabilized and then the load is completely removed immediately. The torque is measured by means of angular acceleration shortly after the engine is unloaded. By this, the effective torque is obtained without the transmission losses, which then appear in the final equation in the form of mechanical transmission efficiency. This method of measurement is more accurate than dynamometer measurements.

2.2 Data measured during vehicle travel

As an example we have selected two readings on FAVORIT 136 L. During the first measurement, denoted by the index 1, the vehicle was loaded with three persons and standard equipment including fuel in the tank. Before the second measurement (denoted with index 2) the person weighing 106 kg left the vehicle while all the other conditions remained identical. In the two presented measurements at times I =1 and I =2, the following readings were taken:

$\mathbf{mv_1 = 1209}$ and $\mathbf{mv_2 = 1103}$ [kg] are the static weights of the vehicle for measurements 1 and 2, measured on weigh scales before the test (these values were used to assess the results obtained from the in-vehicle dynamic measurement).

$\mathbf{n_1 = 2357}$ and $\mathbf{n_2 = 2501}$ [min^{-1}] are the frequencies of crankshaft rotations during measurements 1 and 2.

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

$\mathbf{v_1 = 48.78}$ and $\mathbf{v_2 = 51.79}$ [$\mathrm{km.h}^{-1}$] are the linear velocities of the vehicle during measurements 1 and 2, determined from the frequency of drive wheels rotation (this can also be measured telematically).

$\mathbf{a_1 = 0.959}$ and $\mathbf{a_2 = 1.065}$ [$\mathrm{m.s}^{-2}$] linear acceleration of the vehicle during measurements 1 and 2, obtained by derivation of speeds v_1 and v_2 against time (this can also be measured using a gravity sensor).

$\boldsymbol{\alpha_1} = \mathbf{-1.1}$ and $\boldsymbol{\alpha_2} = \mathbf{-1.1}$ [%] is the percentage elevation angle of a given section of the road, i.e. 100.tangent.$\boldsymbol{\alpha}$. The value is positive uphill and negative downhill. (measured using inclinometer and taken as the mean value for the road section).

$\mathbf{vx_1 = 1.8}$ and $\mathbf{vx_2 = -2.5}$ [$\mathrm{km.h}^{-1}$] is the perpendicular projection of the wind velocity vector to the longitudinal axis of the vehicle (i.e. speed of wind in the direction of the vehicle's longitudinal axis; measured using anemometer as the mean value for a given section of the vehicle trajectory). The value is positive in the direction of the vehicle drive and negative in the opposite direction.

Note: In the presented experiments the wind velocity and direction were measured outside of the vehicle. Then by comparing with the instantaneous velocity of the vehicle the relative velocity of wind in the direction of the vehicle's longitudinal axis was being calculated. This enabled to investigate the effect of perpendicular component of the wind, which proved to be insignificant. A sensor of relative velocity of wind installed on the vehicle is to be used for practical applications.

Figures 2 to 5 illustrate the measured data and primary data processing for the given case.

2.3 Calculation of dynamically measured vehicle weight

In any time in any driving regime, all the forces acting on the perimeter of the vehicle drive wheels are in equilibrium. Under the condition of ignoring all the insignificant components of the given forces, e.g. effects of engine and transmission oil temperature, effects of air pressure, temperature and humidity, road surface adhesion properties etc., we can obtain the following equation for calculation of the vehicle's weight-in-motion:

$$m_i := \frac{\dfrac{ip \cdot up}{Ra} \cdot M(n_i) - a_i \cdot \left(\dfrac{ip^2 \cdot Im}{up \cdot Ra^2} + \dfrac{Ia + Ib}{Ra^2} \right) - \dfrac{0.5 \cdot \rho \cdot cw \cdot SP}{3.6^2} \cdot (v_i - vx_i)^2}{a_i + \left(ka + \dfrac{v_i}{3.6} \cdot kb \right) + 9.807 \cdot \sin\left(\operatorname{atan}\left(\dfrac{\alpha_i}{100} \right) \right)} \tag{1}$$

Each of the input values was repeatedly measured to allow statistical compensation of random errors with accuracy given by the number of decimal places. By calculation of the equation 1, relatively accurate results are obtained. The maximum relative error of the dynamic determination of the vehicle weight is in this case roughly equal to 0.6 %. However, it should be noted that the torque characteristic M (n) was updated just before the measurement was conducted. This was done using quasistatic measurement with comparable accuracy of ±0.5 %. It will obviously not be possible to reach such accuracy in normal operational conditions.

3 CONCLUSION

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 those resented in the example. For the torque characteristics M(n), the statistical compensation of random errors is not effective as the characteristic is distorted by systematic errors resulting from gradually increasing occurrence of engine failures.

Basing on the performed measurements and gained experience, the authors expect that the deviations of characteristic M (n) from the normal emerging during the engine operation will typically be negative and not exceeding 10 % of the standard value of the new run-in engine. The given limit of 10 % is so large that it would result in significant drop in power and usability of the vehicle as well as substantial increase of fuel consumption, which would be intolerable for the user.

The obtained results presented in Table 1 demonstrate that the relative errors in dynamic measurements of vehicle weight can be expected to reach roughly 10 %. The presented practical experiments will be extended to other types of vehicles and various measurement conditions. In-vehicle weigh-in-motion systems could be part of the next generation of on-board units that will be connected to vehicle CAN bus and will be equipped with all the necessary components like GPS, GSM, accelerometer, etc.

Tab. 1 Measurement errors of dynamic measurement of vehicle weight

Measured object	Weight (weigh scale) [kg]	Weight (Dynamic measurement) [kg] (*)	Absolute error of dynamic measurement [kg] (*)	Relative error of dynamic measurement [%] (*)
Vehicle – measurement 1	1209	1202.9 (1337)	-6.1 (128)	-0.51 (**10.6**)
Passenger. who left the vehicle	106	105.9 (116)	- 0.1 (10)	**-** 0.1 (**9.5**)
Vehicle – measurement 2	1103	1096.9 (1221)	-6.1 (118)	-0.56 (**10.7**)

(*) maximum inaccurate values

4 REFERENCES

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Pejsa L.. Kadlecek B.. Pexa M.. Hladik T.: Methodology for determining emission production. fuel consumption and technical conditions of Heavy Duty Vehicles using rollers. COST Project Annual Report TF CUA. Prague 2003.

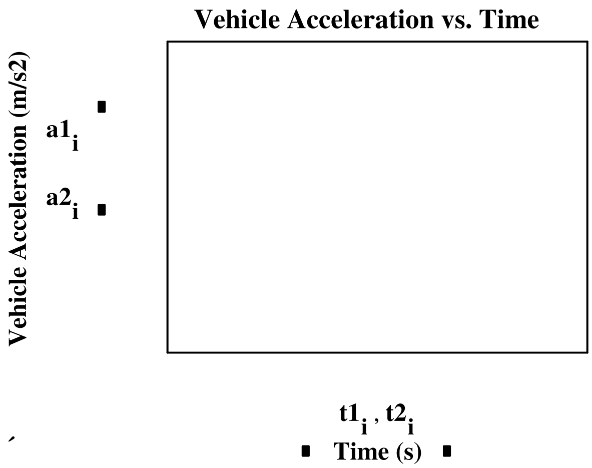

Figure 2. Linear acceleration a_1 and a_2 [m.s^{-2}] of the vehicle during the first measurement (lower curve) and second measurement (higher curve) in relation to time t_1 and t_2 [s].

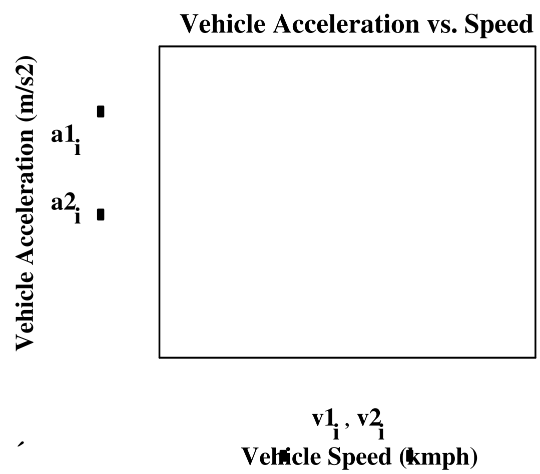

Figure 3. Linear acceleration a_1 [m.s^{-2}] of the vehicle during the first measurement and second measurement in relation to vehicle speed $\mathbf{v_1}$ and $\mathbf{v_2}$ [km.h^{-1}]

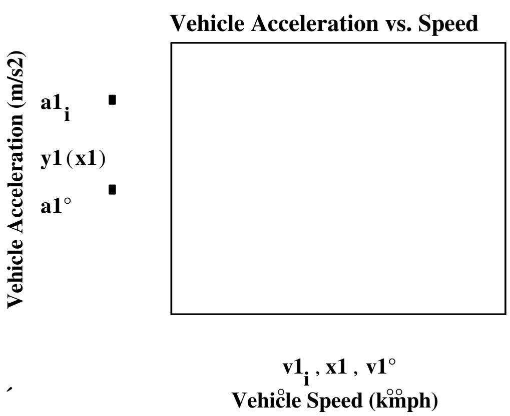

Figure 4. Detail of linear acceleration a_1 [m.s^{-2}] of the vehicle with the regression curve $\mathbf{y_1}$ and its mean value $\mathbf{a_1}$ for the measured road section.

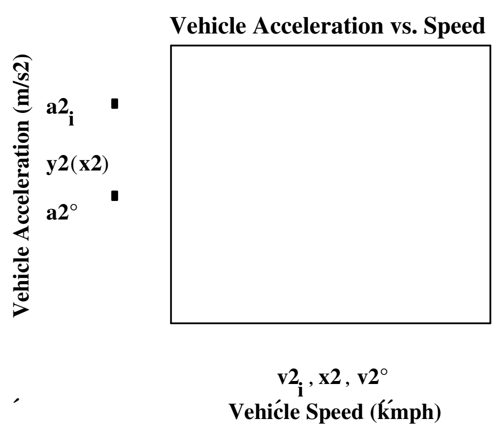

Figure 5. Detail of linear acceleration $\mathbf{a_2}$ [m.s^{-2}] of the vehicle with the regression curve $\mathbf{y_2}$ and its mean value $\mathbf{a_2}$ for the measured road section.