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THE PRECISE MEASUREMENT OF CAR VELOCITY

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Abstract. The system for precise measurement of car velocity is using lasers and reference distance fixed on the car. Primary application for this system is verification and calibration of stationary velocity meters without the need for disassembling or transporting them to testing area. Velocity measurements can be performed under the real traffic conditions. Principle of operation, calibration of the measurement system and uncertainties are provided. Some solutions used in this system operate in a wide range of possible environmental conditions. Additionally, ABS sensors were used for dynamic car velocity evaluation. Possibilities of this system, when used in combination with optical measurements, are provided. Experimental data demonstrates ABS sensor applicability in measurements with different road types, tire pressures and temperatures.

Keywords: car, velocity, measurement, ABS, sensors, calibration.

1. Introduction

Verification and calibration procedure for car velocity meters often requires precision or reference car velocity measurement when measured velocity is verified against known car velocity. Similar procedure is needed especially with stationary velocity meters. Disassembling and installation of stationary velocity meters may affect velocity measurements. Calibration and verification of such equipment on site is preferable. Car standard velocity measurements (needed for verification or calibration) are the primary application for this system.

Velocity measurement with microwave radar may be using time of flight, Doppler methods (Winkler 2007). These methods usually suffer from high beam divergence which limits applicability, causes poor angular resolution, cosine effects and usually lacks in precision needed for calibration. Optical velocity determination methods may be laser Doppler, spatial filtering, laser-speckle, laser time of flight methods. These methods have high angular resolution. Laser Doppler which was proposed by Yeh and Cummins (1964), spatial filtering which was proposed by Ator (1966) and laser-speckle which was proposed by Stavis (1966) velocity measurement methods are dependant on road conditions, which makes these methods limited in their application especially on wet roads. Laser time of flight or laser Doppler (pointed at car) velocity measurements (Amann *et al.* 2001) may have some limitations, but also sufficient precision. Systems having suitable parameters may be complex. Unfortunately all these measurement methods require complex calibration. The problem is that up to now calibration methods or benchmark equipment for parameter calibration under real traffic conditions are limited in their application. Some road areas are not suitable for the equipment, traffic conditions may interfere with measurements, etc. Usage in previously unsuitable areas, possibility to use measurement system under heavy traffic conditions and simplified site preparation are the main advantages for this measurement system.

Velocity (V) measurement is based on distance (X) and time (t) measurement, one of which can be constant and known in advance using simple relationship:

$$V = \frac{X}{t}. \tag{1}$$

Usually distance is constant (reference distance). It makes two possibilities available:

- car is moving through reference distance;
- reference distance is fixed on the car and moving with it.

Car moving through reference distance used in other designs (Žilinskas 2010) is usually used in measurements on initially prepared site. Design using reference distance moving with a car was used for this measurement system. Properties of this measurement system will be discussed in detail.

Car velocity is not constant, and is changing according to: road, car tires, wind, etc. Measured velocity is average velocity within reference distance and it can be close to momentary velocity if reference distance is short enough. Relatively short reference distance allows this measurement system to be used in car dynamic measurements using multiple lasers.

Car velocity change is measured using signal from ABS sensors. ABS sensors allow tracking of velocity changes during measurement without the need for additional lasers and allow to extend measurement range of the measurement system at the expense of lower precision that ABS sensors with advanced signal processing may offer. Velocity uncertainties are experimentally evaluated along with effects that influence ABS sensor measurements.

2. Velocity Measurement System

Velocity measurement system consists of: measurement block, laser, personal computer and additional interface for ABS sensor signal (Fig. 1).

Personal computer is interfaced using USB or wireless Bluetooth. Wireless connection is preferable when ABS is not used and no wires are needed. Measurement block should be fixed on a car with its axis parallel to the car movement axis (Fig. 2). Measurement block is aligned so that it is parallel to the road and to the longitudinal axis of the car or is as close to it as possible.

Optical sensors are located 1m apart in a measurement block. Laser is placed on a roadside and is directed towards measurement block. Laser beam is focused and spread into the line using cylindrical lens and falls into optical sensor through 2 mm wide opening when the car is moving.

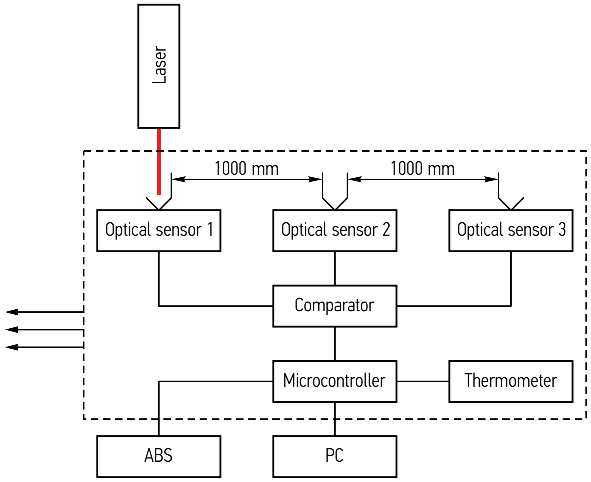

Fig. 1. Block diagram of measurement system

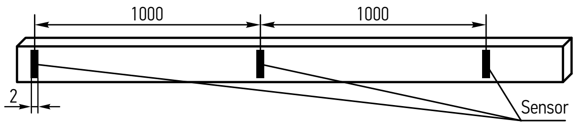

Fig. 2. Schematics for optical sensor placement

Preparation for velocity measurement consists of a laser placing and positioning on roadside. Placed laser beam line has to be vertically aligned and parallel to optical sensor opening or has to be as close to it as possible. During the experiment, laser placement and positioning was done in less than 1 min, because laser does not have to be perpendicular to the car's movement trajectory (Fig. 3). Car preparation is not taken into account as it is done only once prior to all measurements.

Optical sensors' response to light is maximally close to linear and this makes it much less sensitive to surrounding light conditions. Signal voltage is directly proportional to light power entering optical sensor. Filtered and amplified sudden changes of a signal are used for velocity measurement. Comparator is used to trigger time measurements of events when light intensity starts exceeding certain threshold (laser beam is detected by optical sensor) and when light intensity falls lower than a certain threshold (laser beam no longer detected by optical sensor) (Fig. 4).

One laser beam passing through two optical sensors gives four time events t_1, t_2, t_3 and t_4 which correspond to positions x_1, x_2, x_3 and x_4 (Fig. 4).

If laser beam light intensity is symmetrical and distance between sensor's optical centres is known, velocity can be calculated:

$$V = \frac{2 \cdot X}{t_4 + t_3 - t_2 - t_1}. \tag{2}$$

With 3 light sensors it is possible to evaluate the stability of the acceleration or velocity. Velocity stability can be calculated as two different velocities are available. Acceleration can also be used as an indicator of velocity stability. Distance between light sensors is close to 1 m (Fig. 2). The exact distance is measured during calibration. Calibration takes optical effects into account and optical distances are found.

This car velocity measurement method is not dependant on horizontal car velocity direction or angle, because reference distance is moving along with a car.

Fig. 3. System for precise velocity measurement with laser

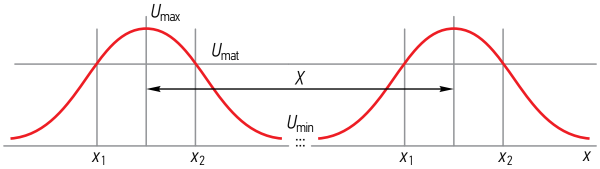

Fig. 4. Optical sensor signal

Extreme car velocity angles, that may significantly broaden laser line width, do not affect measurement as light sensors are directional and rule out such conditions. Measurement can only be affected by direction changes during measurement. These effects are limited by car dynamics and directional light sensors. Additional monitoring of ABS sensor signal can detect changes of direction during measurement. ABS sensors were used in experimental setup to evaluate car dynamics during measurements and determine existence of possibly improper conditions.

Measurement block has a frame made from aluminium alloy which can be affected by different temperatures. Thermometer is used to constantly monitor temperature and compensate for effects of thermal expansion that affects distance X:

$$\frac{\Delta X}{X} = \alpha_L \cdot \Delta T, \quad (3)$$

where: α_L is thermal expansion coefficient; ΔT is temperature difference (from calibration temperature); ΔX distance change. For aluminium alloy used in experimental measurement system $\alpha_L = 23 \cdot 10^{-6}$ °C^{-1}.

With thermal compensation it is capable to operate in wide range of temperatures (from –20°C to 60°C). Limitation for temperature range, in this case, is coming from electronic components (Li-ion battery) and may be extended using different set of components.

3. Calibration

Calibration of this measurement system is performed by calibrating distances between sensor optical centre points and calibrating time measurement.

Distance calibration of experimental measurement system was performed using 'Global Status' distance calibration device. Achievable calibration uncertainty of this device is –3.2 µm / +2.1 µm.

Time is calibrated using external reference signal (Fig. 5). The same setup is used for a signal imitation and experimental determination of delay parameters. Time measurement is one of the least influential factors in velocity measurement.

Calibration of measurement system makes uncertainties in time and distance insignificant to the overall uncertainty of velocity. Major uncertainty comes from car movement vector and measurement block axis misalignment. Possible axis misalignment up to 50 mm at measurement block's (which has length of 2 m) end is taken as a maximal allowable value. The last sensor should not pass the same laser beam with spatial displacement exceeding 50 mm from the position of the first sensor (when it was passing laser beam). To ensure these requirements separate measurements were made using inclinometer PMP-S20HT and accelerometers LIS344ALH, ADXL210.

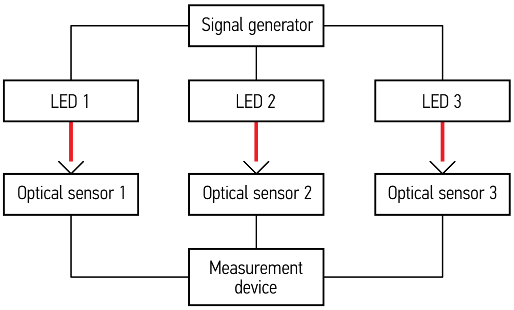

Fig. 5. Frequency calibration and laser beam light imitation

Theoretical evaluation of uncertainty, gives velocity uncertainty in the range of +0.037% / –0.014%.

4. ABS Sensor Usage for Velocity Evaluation

Additional ABS sensor signal is used to monitor car velocity and direction changes constantly. ABS sensors give additional information about dynamic velocity changes which are used to track car dynamics during measurement and detect improper measurement conditions.

In normal drive condition, car velocity is almost the same as wheel velocity (Jiang, Gao 2000). Tire rotation is often used to measure both velocity and distance. These measurements are usually done using sensors or mechanical means through gearbox. To utilize measurements with improved precision direct wheel rotation measurement is preferable. This makes usage of ABS reasonable as it already has rotation sensors in all wheels. By using signal from ABS sensors it is possible to track all wheels separately. Calibration or verification of stationary velocity meters takes place only with straight car trajectories. Straight car trajectories make tire slipping less influential and precision velocity measurement is possible. Signal from all wheels makes it possible to detect straight trajectory, evaluate slip. ABS sensors are used in combination with optical measurements or at least have to use one optical measurement for calibration purposes.

ABS sensor signal is used directly by microcontroller through ADC synchronized with timer. This timer is also making time measurements of optical sensor events. Microcontroller sends out raw ABS sensor signal data to PC where digital filtering and signal processing is performed.

Tire dynamics model (Fig. 6), has parameters: R_g – geometric or unloaded radius, R_h – loaded radius, R_ω – effective or rolling radius, ω – tire print radius or tire contact angle (Jazar 2008).

Parameters that can be easily measured (R_g, R_h), are used to calculate effective radius using (Jazar 2008):

$$\cos\varphi = \frac{R_h}{R_g}; \quad (4)$$

$$R_\omega = \frac{R_g \sin\varphi}{\varphi}. \quad (5)$$

With these equations it is possible to calculate coarse effective tire circumference:

$$P_\omega = 2\pi R_\omega. \quad (6)$$

This value is approximate and can be used only for coarse distance, velocity evaluation. Precise measurements require much higher precision of effective radius or tire circumference under the real conditions, than this model can provide, as tire profile does not fit exactly into

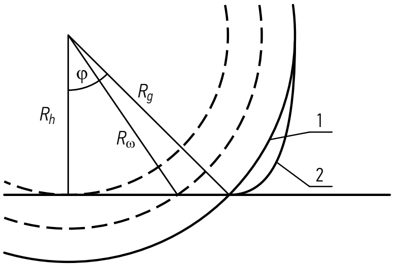

Fig. 6. Tire: 1 – idealized tire profile; 2 – real tire profile

idealized circle (Fig. 6). Effective tire radius may change from temperature, tire pressure or road type. Radial tires also may have different relationships.

The vertical stiffness of radial tires is less than non-radial tires under the same conditions. So, the loaded height of radial tires R_h, is less than the non-radials'. However, the effective radius of radial tires R_ω, is closer to their unloaded radius R_g (Jazar 2008). It makes it reasonable to use additional precise velocity measurement which can be used to evaluate effective tire circumference and use it as long as external influences do not change it significantly. External influences with different types of tires may of a different magnitude and these effects can be analyzed using combined optical and ABS sensor measurements.

The main parameter which is used to calculate velocity from tire rotation is effective tire circumference (tire circumference later). Experiments were performed using radial tires 195/65 R14 (theoretical unloaded tire circumference $P_g = 1.9135$ m). Two experiments were carried out on asphalt road at different temperatures. The first was performed when ground temperature was 21.6°C, tire temperature rose from 24.9°C to 32°C during experiment. The second, when ground temperature was 12.5°C and tire temperature rose from 19.7°C to 24.8°C. Both experiments were carried out using 2 tire pressures on different roads and different days with different weather conditions. Experiment on gravelled road was carried out using only one tire pressure and road temperature was 6.2°C, tire temperature 20.8°C. Tire circumference is calculated by measuring velocity, using optical system and calculating time of full tire rotation from ABS sensor signal. Optical speed measurement gives average speed over 2 m. Full tire rotation gives average speed over length close to effective tire circumference. Speed changes over short distances (difference of these two lengths) are not significant to the overall result and optical speed measurement can be used directly to calibrate tire rotation giving exact value of effective tire circumference. Car in experiment was driving freely through measurement lasers with engine disconnected from driven wheels (neutral gear, etc.). Measurements for single tire on 3 different roads can be seen in (Fig. 7).

The following data shows no significant changes in tire circumference (that influences velocity measurement using ABS sensors) with different tire pressure and different velocity. Scattering of the result (Fig. 7) can indicate that changes from temperature or pressure in these experiments are close or below the uncertainty of a single measurement limit. Average tire circumference $P_\omega = 1.8527 \pm 0.0058$ m, $p = 0.95$ which corresponds to 0.31% uncertainty. Road conditions slightly differ during 4 tests on asphalt road and have 0.25% uncertainty, 0.37% on gravelled road. Road temperature influence is relatively small and its significance still must be verified through more extensive experiments. Velocity insensitivity to tire pressure can be explained by rigidity of tread which is reinforced with ply cords and may vary with different tires.

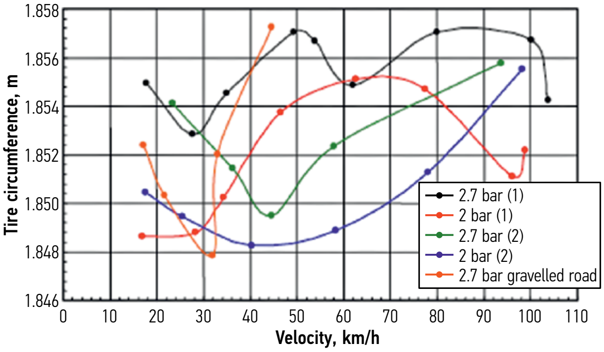

Fig. 7. Experimental ABS sensor data with various tire pressures and different road temperatures

ABS signal can be used to determine velocity where laser coverage is not available. ABS sensors are less precise in velocity measurement. In order to improve measurement accuracy, system consisting of multiple lasers is possible. In some cases important value is velocity stability, which can vary (Fig. 8). ABS sensors for left and right wheel are used in figures. The first optical measurement is used for calibration, the second for verification purposes. Car was driving freely without engine thrust or brakes through both lasers.

Different velocities have different ABS sensor reactions to similar road profile which can be seen (Figs 8 and 9). Uneven road profile between two optical measurements influences velocity changes and tire rotation changes that can be seen in figures.

Gravelled road may influence velocity measurement using ABS. Experiment was carried out on gravelled road. Road temperature was 6.2°C. Tire temperature 20.8°C (Fig. 10).

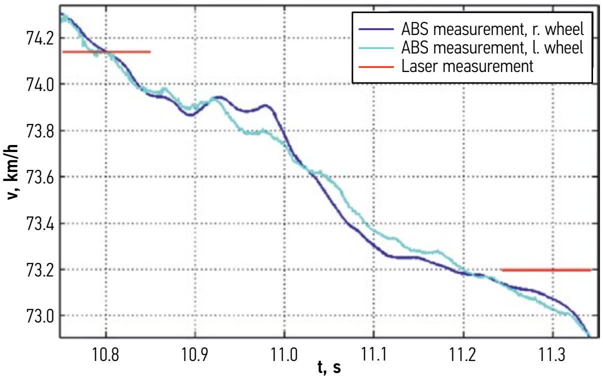

Fig. 8. Experimental ABS sensor data, car velocity

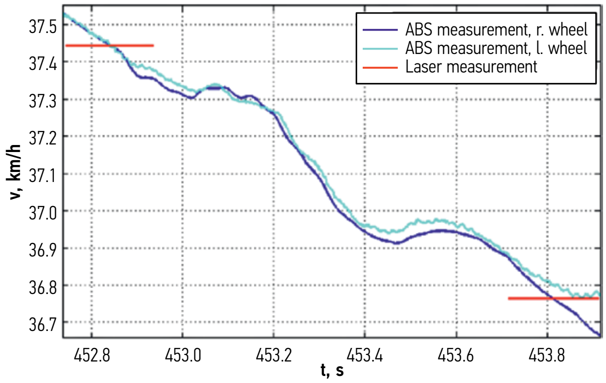

Fig. 9. Experimental ABS sensor data, car velocity

Gravelled road covered with snow may influence ABS sensor measurements too. Road temperature was –8.7°C. Tire temperature 3.8°C (Fig. 11).

Modelling of tire-road interaction Rutka and Sapragonas (2002) concludes – it was determined that a tire does not fully smooth the irregularities of a surface texture level.

Experimental data was used to verify velocity measurement dependence on road type. Gravelled road causes more vibrations in tire. These vibrations cause more uneven rotation of tire and velocity measurement. Vibration effects are diminished by signal processing, using only complete tire rotations, but still can be seen (Figs 10 and 11). Experimental data indicates, that gravelled road causes slightly higher uncertainties of velocity measurement (Fig. 7).

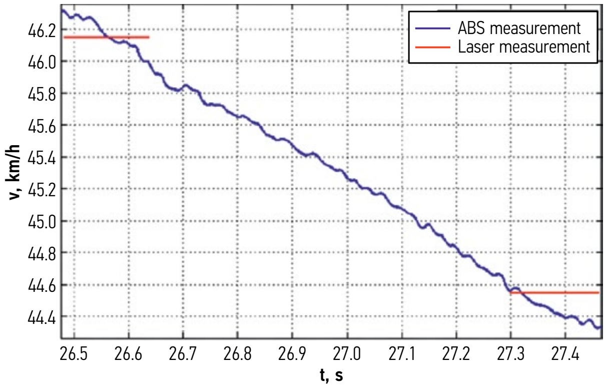

Fig. 10. Experimental ABS sensor data, car velocity on gravelled road

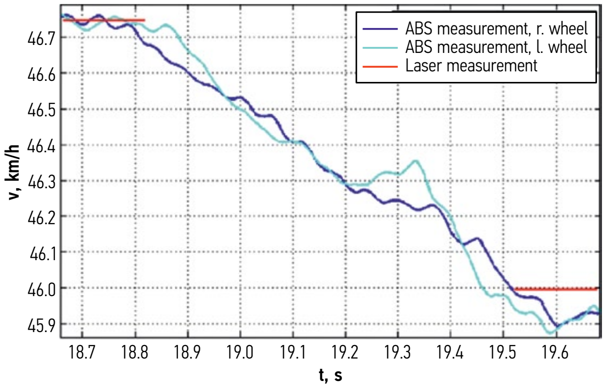

Fig. 11. Experimental ABS sensor data, car velocity on gravelled road covered with snow

ABS sensors, when used in combination with precise optical velocity measurement system, can give additional dynamic velocity data and be used to track velocity over longer distances than it is covered by lasers.

5. Conclusions

1. Car standard velocity measurement system needed in verification and calibration of velocity meters under the real traffic conditions was implemented by using distance reference fixed on moving car.
2. Optical measurement system can measure car velocity from 10 km/h to 200 km/h at temperatures of –20°C … 60°C, achieves measurement uncertainty close to theoretical +0.037% ... –0.014% and can be used for calibration, verification purposes.
3. Measurement system was designed so, that preparation time would be minimal. The time for system preparation during a test did not exceed 1 min. Measurement system can be used in a wide range of climatic situations, is waterproof, and does not depend on road condition or type as long as it does not cause increased vertical displacements of car.
4. Additional ABS sensor usage after calibration can be used for dynamic velocity measurement and achieves uncertainty close to 0.25% on asphalt and 0.37% on gravelled road. Experimental data shows that temperature and tire pressure influences are minimal and did not exceed 0.37% under normal driving conditions.
5. Experimental data shows that ABS sensors can be used to extend measurement range over longer distances than it is covered by lasers at the expense of increased uncertainty.

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