**International Journal of Mechanical Engineering and Technology (IJMET)**
Volume 9, Issue 11, November 2018, pp. 1997–2005, Article ID: IJMET_09_11_210
Available online at http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=9&IType=11
ISSN Print: 0976-6340 and ISSN Online: 0976-6359



# VIRTUAL SENSORS OF LIVE MONITORING SYSTEM OF VEHICLE MOTION VARIABLES

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**ABSTRACT**

*The issue of safe traffic is an urgent current problem of global prominence. The importance of the studies aimed at development of efficient prevention of road accidents and analysis of causes of motor vehicle collisions (MVC) is determined by necessity to improve the traffic safety. The purpose of this work is estimation of possibilities of virtual data sensors which form the center of live monitoring system of vehicle motion variables. Virtual sensors are based on indirect measurements involving mathematical models and algorithms for ill-posed problems. The set of variables required for prevention of collisions was determined by conditions of prevention of typical collisions of structured set. This problem is reduced to dynamic stabilization in the most general algorithmically solvable formulation. The use of virtual sensors for its solution makes it possible to reduce significantly the number of physical data sensors of variable state and to improve nearly all consumer performances of live monitoring system. The novelty of the work is in confirmation of metrological properties of virtual data sensors operating in minimum configuration of supplemental engineering tools.*

**Keywords:** Live Monitoring System, Virtual Data Sensor, Mathematical Model, Algorithm For Ill-Posed Problems.

**Cite this Article:** Sergei Evgenevich Buznikov, Andrei Mikhailovich Saikin, Dmitrii Sergeevich Elkin and Vladislav Olegovich Strukov, Virtual Sensors of Live Monitoring System of Vehicle Motion Variables, International Journal of Mechanical Engineering and Technology, 9(11), 2018, pp. 1997–2005.
http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=11

## 1. INTRODUCTION

The issue of safe traffic is an urgent current problem of global prominence, it relates vital concerns of all members of civilized world. Global importance of this issue is determined by the fact that its solution always attracts attention of governmental and social organizations. Leading car manufacturers improve systems of active and passive safety as well as equip the manufactured vehicles with regular live monitoring systems of motion variables and recording of collision parameters upon road accidents [1]. The following devices are quite often installed on vehicles: tachographs [2], video cameras [3], satnav systems [4], and other monitoring systems.

In order to obtain objective estimation of MVC conditions, it is planned to apply "black boxes" [5-7], automatic recording of accident place [8], and emergency calls.

At present there is no general consensus concerning the motion variables which should be recorded in order to obtain adequate MVC pattern, as well as which development principles of live monitoring systems should be used.

This work is aimed at estimation of metrological capabilities of virtual data sensors of live monitoring system of vehicle motion variables.

## 2. METHODS

The issue of collision prevention [9] is reduced to the problem of dynamic stabilization of vehicle state variables:

$$x_{i\text{bound}}^{L}(X,U,t) \leq x_i(t) \leq x_{i\text{bound}}^{U}(X,U,t), 1 \leq i \leq n \text{ at } U \in U_{\text{perm}}, \quad (1)$$

where $X = (x_1 \ldots x_n)^T$ is the state vector; $x_i(t), 1 \leq i \leq n$ is the i-th component of the state vector $X$ of n dimensions; $x_{i\text{bound}}^{L}(X,U,t)$ is the lower boundary of the i-th component of the state vector $X$; $x_{i\text{bound}}^{U}(X,U,t)$ is the upper boundary of the i-th component of the state vector $X$; $U$ is the vector of control action on controls including draft, brakes, steering, and gearbox; $U_{\text{perm}}$ is the permissible region of control actions.

Components $x_i$ of the state vector $X$ and their boundaries are determined on the basis of sufficient conditions of prevention of typical collisions of structured set.

Vehicle live monitoring systems (LMS) are intended for recording and logging of vehicle motion variables and driver actions both upon MVC, and for information support of decision making by driver in the course of accident-free operation. In addition, it becomes possible to analyze the LMS operation logs aiming at revealing of possible road traffic offences during overall vehicle lifetime.

Analysis of prevention of typical collisions demonstrates that the components of the vector $X$ are as follows:

$V_m$ – the velocity of longitudinal motion of mass center;
$\Psi_c$ – the angle of steered wheels;
$L_m$ – the covered distance;
$V_i, 1 \leq i \leq 4$ – the longitudinal rotation rates of wheels;
$\Delta V_{Si}, 1 \leq i \leq 4$ – the rates of wheel longitudinal slip;
$\Delta\omega_m$ – the additional angle rotation frequency of mass center upon wheel yaw and drift;
$P_i, 1 \leq i \leq 4$ – the air pressure in tires;
$T_{Bi}, 1 \leq i \leq 4$ – the brake overheating temperature;
$T_{Ti}, 1 \leq i \leq 4$ – the tire overheating temperature;
$\Delta R_{ki}, 1 \leq i \leq 4$ – the tire cord wear;
$\Delta X_i, 1 \leq i \leq 4$ – the misalignment of wheels and hubs;
$\Delta P_{Ti}, 1 \leq i \leq 4$ – the thermal components of air pressure in tires;
$k_{Si}^{*}, 1 \leq i \leq 4$ – the top values of friction coefficients of wheel slip;
$D_S$ – the additional toe angle of wheels;

$L_x$ and $L_y$ – the coordinates of mass center in Cartesian coordinates;

$\Psi_m$ – the angle course;

$\Delta H$ – the deviation of vehicle mass center from traffic lane center;

$\Delta L_1$ and $\Delta L_2$ – the distances to the nearest front and back obstacles on traffic lane [10].

The mathematical model for designing virtual sensors of motion variables was based on the mathematical model of vehicle wheel rotation on turns:

$$\begin{cases} V_1 = V_m + 0.5a_1 b^{-1} V_m \Psi_c + \Delta V_{S1} + 0.5a_1 \Delta\omega_m; \\ V_2 = V_m - 0.5a_1 b^{-1} V_m \Psi_c + \Delta V_{S2} - 0.5a_1 \Delta\omega_m; \\ V_3 = V_m + 0.5a_2 b^{-1} V_m \Psi_c + \Delta V_{S3} + 0.5a_2 \Delta\omega_m; \\ V_4 = V_m - 0.5a_2 b^{-1} V_m \Psi_c + \Delta V_{S4} - 0.5a_2 \Delta\omega_m, \end{cases} \quad (2)$$

where $a_1$ and $a_2$ were the front and rear wheel gauge, respectively; $b$ was the vehicle wheel base.

If solution of the direct problem of determination of $V_i$ by the known terms in the right side of Eq. (2) is trivial, then the reverse problem of determination of the terms in the right side by the known $V_i$ is ill-posed.

## 3. RESULTS

In order to transform this problem into the well-posed problem, it is required to introduce predetermining conditions.

The predetermining conditions are as follows:

- Consistency of signs of longitudinal acceleration and longitudinal velocities of wheel slipping:

$$\begin{cases} \text{If } a_m \geq 0, \text{then } \Delta V_{Si} \geq 0, 1 \leq i \leq 4; \\ \text{If } a_m < 0, \text{then } \Delta V_{Si} \leq 0, 1 \leq i \leq 4. \end{cases} \quad (3)$$

- Limitation of longitudinal acceleration:

$$a^L_{\text{bound1}} \leq a_m \leq a^U_{\text{bound1}} \quad (4)$$

- Determinacy of the value and the sign of angle frequency of wheel yaw and drift:

$$\begin{cases} \text{If } V_m \leq \min[V_{bound1}, V_{bound2}], \text{then } \Delta\omega_m = 0; \\ \text{If } V_{\text{bound1}} > V_{bound2} \text{ and } V_m > V_{bound2}, then\ sgn(\Delta\omega_m) = sgn(\hat{\Psi}_c); \\ \text{If } V_{\text{bound2}} > V_{\text{bound1}} \text{ and } V_m > V_{bound1}, then\ sgn(\Delta\omega_m) = -sgn(\hat{\Psi}_c), \end{cases} \quad (5)$$

where $V_{bound1}$ and $V_{bound2}$ are the boundary velocities of wheel yaw and drift, respectively;

$V_{bound1} = Re\sqrt{2[m_{12}gb - R_d a_{dT}]k_{sq}|\Psi_c^{-1}|}$;
$V_{bound2} = Re\sqrt{2[m_{34}gb + R_d a_{dT}]k_{sq}|\Psi_c^{-1}|}$; $m_{12}$ and $m_{34}$ are the relative distribution of mass on wheels of front and rear axles; $R_d$ is the dynamic wheel radius; $a_{dT}$ is the tractive and breaking acceleration; $k_{sq}$ is the coefficient of slipping friction in transversal direction.

In this case the variables' estimations are as follows:

$$\hat{V}_m(k) = V_m(k) + 0.5[\Delta V_{Si}(k) + \Delta V_{Sj}(k)], \quad (6)$$

where $|\Delta V_{Si}(k) + \Delta V_{Sj}(k)| = \min\,[|\Delta V_{S1}(k) + \Delta V_{S2}(k)|, |\Delta V_{S3}(k) + \Delta V_{S4}(k)|, |\Delta V_{S1}(k) + \Delta V_{S4}(k)|, |\Delta V_{S2}(k) + \Delta V_{S3}(k)|]$.

$$\hat{\Psi}_c(k) = \Psi_c(k) + a^{-1} b V_m^{-1}(k)[\Delta V_{Si}(k) - \Delta V_{Sj}(k)] + b V_m^{-1}(k)\Delta\omega_m(k) \quad (7)$$

$$\Delta\hat{\omega}_m(k) = \begin{cases} 0, if\ \hat{V}_m(k) \le V_{bound1}\ and\ \hat{V}_m(k) \le V_{bound2}; \\ b^{-1}\hat{V}_m(k)\left[\hat{\Psi}_c(k) - |\Psi_{bound2}| sgn(\hat{\Psi}_c)\right], if\ V_{bound1} > V_{bound2}\ and\ \hat{V}_m(k) > V_{bound2}; \\ -b^{-1}\hat{V}_m(k)\left[\hat{\Psi}_c(k) - |\Psi_{bound1}| sgn(\hat{\Psi}_c)\right], if\ V_{bound2} > V_{bound1}\ and\ \hat{V}_m(k) > V_{bound1}. \end{cases} \quad (8)$$

$$\Delta\hat{V}_{Sr}(k) = \begin{cases} (\Delta V_{Sr}(k) - \Delta V_{Si}(k)), if\ r - uneven\ and\ \hat{\Psi}_c \ne 0; \\ \left(\Delta V_{Sr}(k) - \Delta V_{Sj}(k)\right), if\ r - even\ and\ \hat{\Psi}_c \ne 0; \\ \Delta V_{Sr}(k) - 0.5\left(\Delta V_{Si}(k) + \Delta V_{Sj}(k)\right), if\ \hat{\Psi}_c = 0. \end{cases} \quad (9)$$

In order to compensate the non-zero velocities of longitudinal slips $\Delta V_{Si}$ and $\Delta V_{Sj}$ their estimations $\Delta\hat{V}_{Si}$ and $\Delta\hat{V}_{Sj}$ are to be determined additionally in accordance with typical dependence pf slipping friction forces and tractive–braking forces.

In order to estimate the air pressure in tires, let us present the pressures $P_i$, $1 \le i \le 4$ in the form of polynomial:

$$P_i = P_{iH} - \Delta P_i + \Delta P_{Ti}, \quad (10)$$

where $P_{iH}$ is the rated nominal pressure in the i-th tire; $\Delta P_i$ is the deviation from the rated value in the i-th tire; $\Delta P_{Ti}$ is the thermal constituent of pressure in the i-th tire.
Let us present the free radius of the i-th tire in the form of:

$$R_{ci} = R_{ci}(0) + k_1 P_i + k_1 k_v V_i^2, \quad (11)$$

where $k_1$ and $k_v$ are the coefficients of tire linear expansion under the action of pressure and centrifugal forces, respectively; $R_{ci}(0)$ is the free radius of the i-th tire under zero excessive pressure $P_i$.

Let us estimate the free radius: $\hat{R}_{ci} = R_{ci} + k_1\Delta P_i$, which corresponds to the absence of pressure deviation ($\Delta P_i = 0$).

Introduction of estimated velocities of wheel rotation $\hat{V}_i = \hat{R}_{ci}\hat{\omega}_i$ in the left side of the equations will be accompanied by occurrence of pseudo-slips $\Delta\tilde{V}_{Si}$=$k_1\Delta P_i\hat{\omega}_i$ in the right side of Eq. (2).

Resulting estimations of wheel longitudinal slips are $\hat{V}_{Si} = \Delta V_{Si} + \Delta\tilde{V}_{Si}, 1 \le i \le 4$.

Let us introduce additional predetermining condition of existence of zero longitudinal wheel slips:

$$If\ a_{bound2}^L \le a_m \le a_{bound2}^U, then\ \Delta V_{Si} = 0, 1 \le i \le 4, \quad (12)$$

where $a_{bound2}^U$ and $a_{bound2}^L$ are the upper and the lower boundary accelerations of mass center determined by the forces of friction at rest.

In this case the estimated deviation of pressure from the polynomial is $\Delta\hat{P}_i \approx \hat{S}_i k_1^{-1} R_{ci}(0)$, where $\hat{S}_i = \Delta\tilde{V}_{Si} \cdot V_m^{-1}$ is the estimated pseudo-slip of the i-th wheel.

Thermal constituents of $\Delta\hat{P}_{Ti}$ are estimated in accordance with the Charles law for ideal gases as follows:

$$\Delta\hat{P}_{Ti} = P_i(0)(273 + T_{oC})^{-1} \cdot \Delta T_{Ti}, \quad (13)$$

where $P_i(0)$ is the initial pressure in the i-th tire equaling to $(P_{iH} - \Delta P_i)$; $\Delta T_{Ti}$ is the overheat temperature of the i-th tire determined from the solution of the first law of thermodynamics in differential form.

Experimental LMS was tested at Dmitrov testing center in February–March, 2018. VAZ-1117 Kalina with five-stage gearbox was selected for the tests (Fig. 1). Test drives were performed on slip surfaces including snow, ice and their mixt at –10÷ –20°C.


**Figure 1**. Experimental VAZ-1117 Kalina with installed LMS

Figure 2 illustrates indirect measurements of longitudinal velocity of mass center $V_m$ and covered distance $L_m$ as a function of time at standard kilometer. Racelogic satellite system was used as testing equipment.

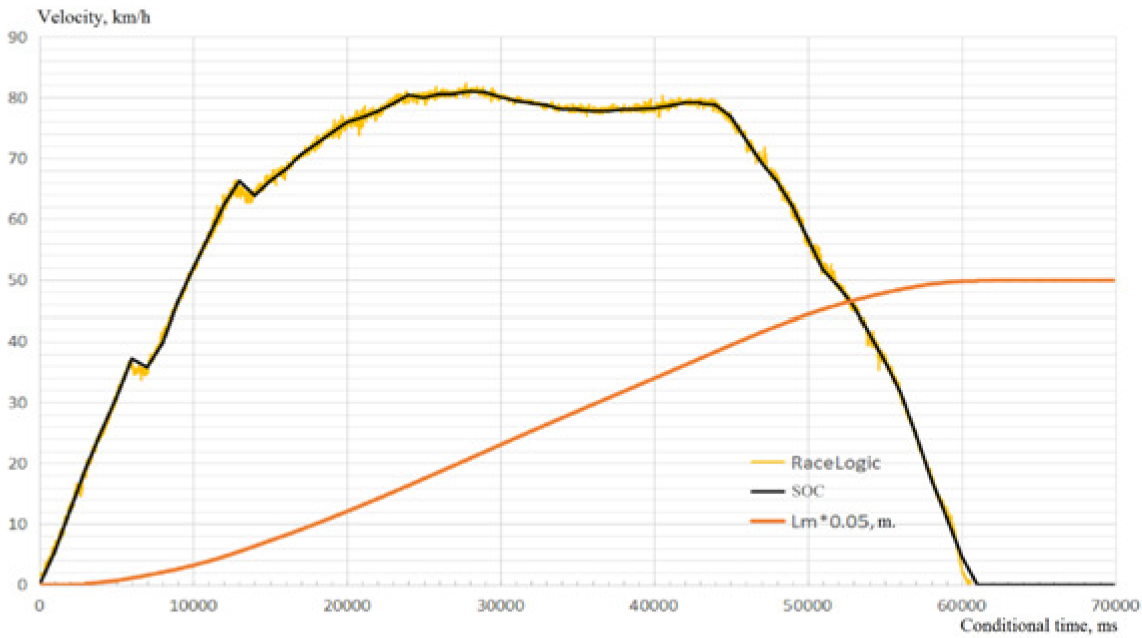


**Figure 2.** Indirect measurements of acceleration to 80 km/h at standard kilometer as a function of time

The acceleration plot highlights the switching from the first to the second gear and from the second to the third gear. Noise constituents of velocity measurements suing the Racelogic system do not measure these events. Error of estimation of longitudinal velocity of mass center determined as the difference of filtered velocities by the Racelogic system and LMS does not exceed 0.1%. The same error levels are for the covered distance $L_m$.

Figure 3 illustrates transversal accelerations measured by virtual LMS sensor and accelerometer control as a function of time.

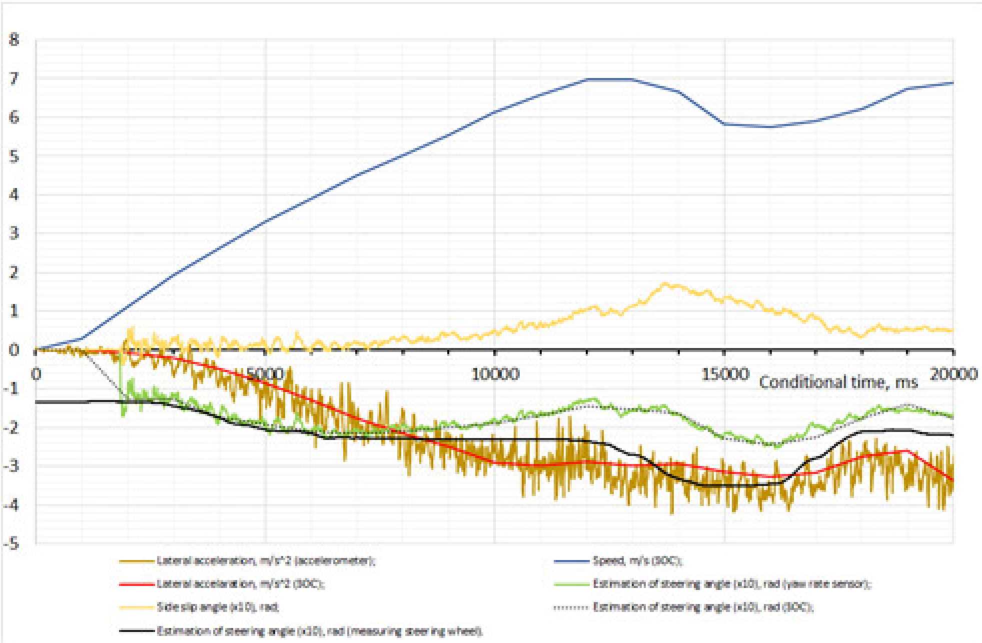


**Figure 3.** Motion variables on turns as a function of time

Estimation errors of transversal acceleration do not exceed 0.05 m/s$^2$, and the angle of steered wheels is less than 0.01 rad. True value of angle of steered wheels was determined by reference sensor of angular velocity of rotation around vehicle vertical axis.

Figure 4 illustrates additional rotation frequency of mass center $\Delta\omega_m$ upon rear wheel yaw on turns as a function of time.

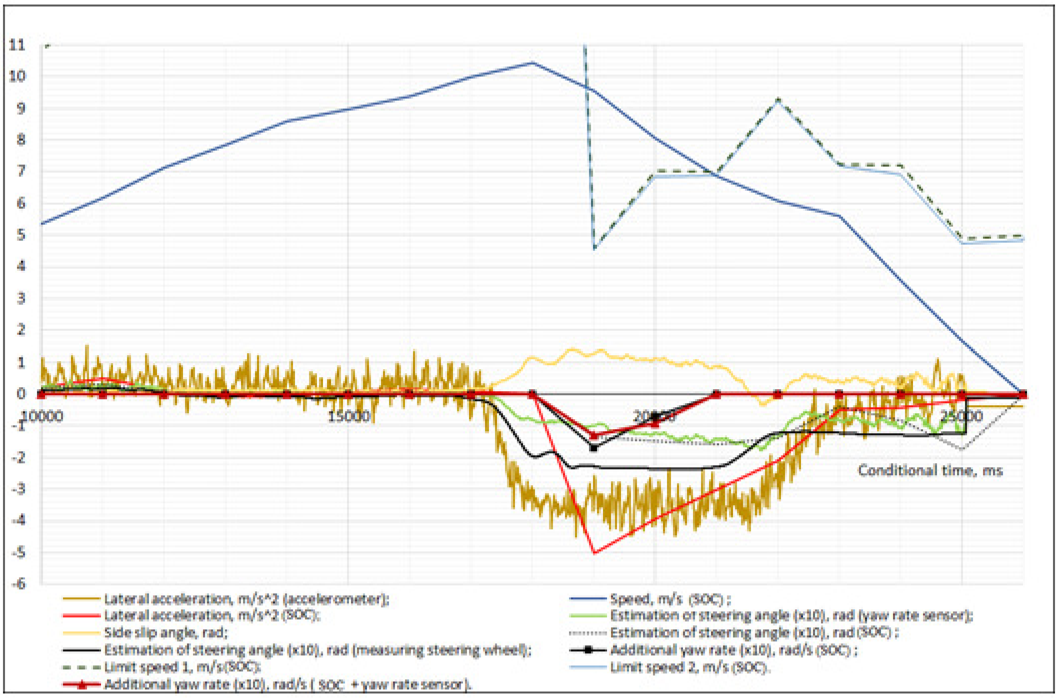


**Figure 4.** Additional rotation frequency of mass center upon yaw as a function of time.

Estimation error of additional rotation frequency does not exceed 0.01 rad/s.

Figure 5 illustrates pressures estimated by virtual LMS sensor for constant pressure deviations from the rated $\Delta P_i$ measured by manometer as a function of time.

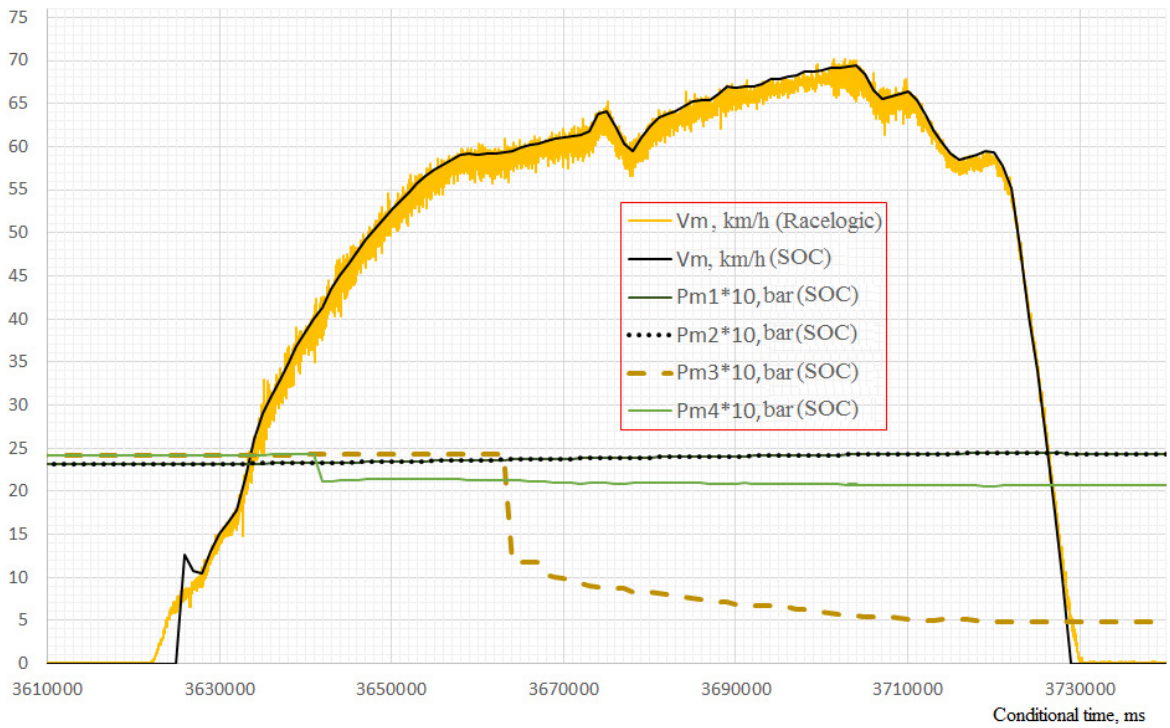


**Figure 5.** Pressures detected by LMS virtual sensors at pressure drops in the 3rd and 4th wheels as a function of time.

Established pressure estimations differ from the preset values not more than by 0.1 bar. Duration of transient mode of pressure estimation is not higher than 60 s, and activation delay of warning about pressure drop more than by 0.3 bar does not exceed 20 s.

## 4. DISCUSSION

Solution of the problem of dynamic stabilization of vehicle state variables, to which the problem of collision prevention is reduced in the most complete solvable formulation, requires for numerous various sensors of primary data. Trivial solution of this problem is reduced to vehicle equipment by additional data sensors, which is accompanied by impairment of nearly all consumer performances including operation expenses and cost of LMS.

Nontrivial solution of the problem is possible upon the use of virtual data sensors based on mathematical models and algorithms of indirect measurements. In this case the number of required data decreases to minimum upon retaining observability of subject and its dynamic boundaries. However, implementation of indirect measurement using mathematical model can be reduced to solution of ill-posed problems. This work discusses conversion of ill-posed problem of estimation of motion variables of mass center and vehicle wheels on the basis of solution of reverse problem for equations of vehicle wheel rotation on turns. Supplemental determination of initial ill-posed problem by subject properties makes it possible to reduce it to well-posed problem and to obtain adequate estimations of mass center velocity, steered wheel angle, longitudinal and transversal accelerations, velocities of longitudinal slips, air pressure in tires, and additional angular frequency of wheel yaw and drift.

Experimental results of LMS in winter season at testing center do not contradict with theoretical considerations and confirm possibility of highly accurate measurements of vehicle motion variables under heavy operation conditions. In particular, errors of indirect measurements of mass center velocity and covered distance do not exceed 0.1%, which is by two orders of magnitude lower than the respective errors of regular speedometers of modern foreign vehicles. Analysis of indirect measurements of steered wheel angle confirms that the obtained estimations include wheel slip angle which cannot be measured by physical sensor of wheel turning angle.

Similar conclusions can be applied to indirect measurements of longitudinal and transversal accelerations, longitudinal velocities of wheel slip, air pressure in tires, and additional angular frequency of wheel yaw and drift.

## 5. CONCLUSION

The following conclusions can be formulated on the basis of the performed studies:

- in order to obtain objective estimation of road accidents' reasons, it is required to have objective information on vehicle motion and on excess of dynamic boundaries of its state by the variables;
- measurement of vehicle motion variables and their dynamic boundaries makes it possible to forecast their violation and to warn driver about approaching to dangerous states;
- indirect measurements of motion variables by means of virtual data sensors facilitate development of LMS with minimum amount of engineering tools;
- the use of information collected in LMS makes it possible to perform objective analysis and to reveal possible road traffic offences during overall vehicle lifetime;
- low cost of LMS and expenses for its maintenance make it possible to install this appliance on vehicles of nearly all price ranges.

## ACKNOWLEDGMENTS

This work was supported by the Ministry of Science and Education of the Russian Federation, Agreement No. 14.624.21.0048. Unique identifier: RFMEFI62417X0048.

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