INVESTIGATION OF THE DRIVER - VEHICLE DYNAMICS

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UDC: 629.1;519.6

INTRODUCTION

Development and construction of modern motor vehicles follow strict requirements to adapt their properties to regulatory - technical and psycho-physiological abilities of drivers. In this regard, it should be pointed out is always current problems of comfort, handling, movement stability, which is reflected in the safety movement. So far, published a number of papers from this issue and made significant efforts to better understand the behavior of drivers in different modes and conditions of movement. In doing so, they used different approaches and methods of research. One of the most commonly used approach to observe the vehicle as an object of control, as part of the control system, the driver-vehicle-environment in which the driver acts as a regulator, [1], [2], [3], [4], [5]. To this end have been developed appropriate mathematical models to describe of the driver control effects. Depending on the control tasks, the structures of these models are single loop or multi loop. Viewing the typical driver models, their relations to the vehicle and the environment, as well as one's own approach to research control system, driver-vehicle-environment, in terms of evaluation and improvement of its performance are presented in the following sections of this paper.

DRIVER MODELS

Conduct research pilot spacecraft started 1940 - these, in terms of modeling their effects, were transferred during 1960 - the study of the behavior of drivers of motor vehicles. During such periods, and later, an important role was played by the concept of quasi - linear model, shown expression (1)

Quasi-linear compensatory model of the driver [4], consists of a describing function component with parameters which depend on the system and driving situation, a set of adjusting elements and an additive remnant,

$$F_D = K\frac{1+T_L s}{1+T_I s}e^{-s(\tau+T_N)} \cong K\frac{e^{-\tau s}}{1+T_N s}\frac{1+T_L s}{1+T_I s} \qquad (1)$$

where: τ - time delay, T_N – the neuromuscular system time lag, $(T_L j\omega+1) / (T_I j\omega+1)$ – equalization characteristic, K – gain factor. The last two characteristics are the major adaptive elements of the driver which allow him to control many different vehicle dynamics. Particularly rational and efficient variant of this model is the so-called, “crossover” model for driver – vehicle open – loop system in region of the crossover frequency.

Generally, drivers use multiple information as input for controlling the vehicle. Good multi-loop system structures are those which no require the driver equalization, for

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example, only gain plus time delay in each of the loops. But driver dynamics as a multi-input system is often approximated by equivalent a single loop system. In the study [9],[11] driver dynamics is described by equivalent closed – loop system which comprising vehicle lateral position and yaw angle feedback loops from corresponding multiple loop. This model is useful to examine the vehicle with 2WS steering system which shows a close correlation between its yaw angle and lateral position response,

The driver block, $F_{D\varepsilon}$, in inner control loop includes, according to (1):

$$F_{D\varepsilon} = K_{\varepsilon}(T_L j\omega + 1)e^{-j\omega\tau} \tag{2}$$

where is, K_{ε} – gain, $T_L j\omega + 1$ – anticipation term for outer loop compensation time lag in vehicle lateral response, τ –time delay. The driver block F_{Dy} is a pure gain feedback for the lateral vehicle deviation. This driver model structure can be suitable base to study changes in driver steering control with learning [9].

Typical transformation multi-loops to single control loop system with the driver in-the-loop can be realized by means driver model concept based on the ″ vehicle inertial lateral deviation advanced in time ″. The model structure in this case assumes that the driver operates on an estimated or projected lateral deviation error. The perceptual preview time, as relation of preview distance, L (look-ahead distance) and vehicle forward speed, results in a pure lead equalization term in the effective vehicle dynamics. Equivalent to ″ lateral deviation advanced in time ″, as distance between sight point S_i, and aim point A_i, is angular deviation, γ as sum of heading angle deviation Δy_{ε} and weighted lateral deviation, Δy, in figure 1:

$$\gamma = K_y \Delta y + \Delta y_{\varepsilon} \tag{3}$$

This driver model concept represents high degree driver perceptual efficiency during driving in the sight field. Instead of perceiving separately the lane position and heading errors in multi-loop control system, perceives only the composite angular error or advanced (projected) lateral deviation in single-loop control system [2], figure 1.

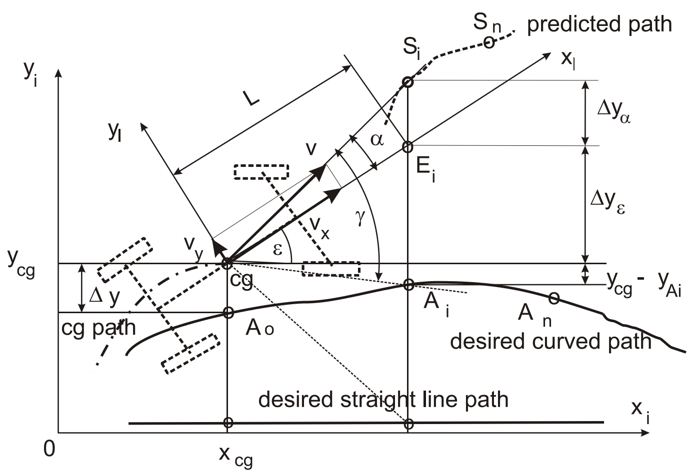


Figure 1 Vehicle position and driver sight field.

Driver can improve the system control performance by using derived path command information in visual field and operating in anticipatory mode. That is, driver can perform the steering task hierarchically into two levels, guidance and stabilization, [6], [7], [8]. In the case of driving into a curve, driver perceives desired path curvature and responds to it an anticipatory open – loop control mode with a part of total necessary steering wheel angle. Based on the perceived path error in closed – loop compensatory mode the driver generates a correcting steering wheel angle.

MODEL OF THE DRIVER - VEHICLE – ENVIRONMENT SYSTEM

Geometric diagrams of a vehicle model following a desired straight line path or a desired curved path, to investigation in this paper, are given in figure 1. As examples are given, single and double lane change, obstacle avoidance, straight line driving: against crosswind, with brake pull, on uneven road and so on. The projection of vehicle center gravity deviation on the look – ahead distance of driver, L, with sight point S_i, in direction of vehicle velocity vector v, is given as distance between points S_i and A_i, for curved path driving,

$$\Delta Y = y_{cg} - y_{Ai} + \Delta y_{\varepsilon} + \Delta y_{\alpha} \cong y_{cg} - y_{Ai} + L\varepsilon + L\alpha \tag{4}$$

and for straight line path driving as,

$$\Delta Y = y_{cg} + \Delta y_{\varepsilon} + \Delta y_{\alpha} \cong \Delta y + L\varepsilon + L\alpha, \qquad y_{Ai} = 0, \quad \Delta y = y_{cg}, \tag{5}$$

where is, L – look – ahead distance of driver, y_{cg}, y_{Ai}, Δy, Δy_{ε}, Δy_{α} – the parts of advanced deviation of vehicle ΔY, caused by vehicle center gravity coordinate, aim point A_i coordinate, vehicle center gravity lateral deviation, vehicle heading angle ε, vehicle side – slip angle, α, respectively.

Vehicle dynamics state space model is selected from presentation of vehicle – sight field interaction in figure 1 and given as follows,

$$\dot{x} = Ax + Bu, \qquad z = Cx \tag{6}$$

where, x = [y, y′, ε, ε′], is the vehicle state variables vector , u = [β, M], is the input vector determined by driver. The output vector, z, can be defined in different forms as a linear combination of the state variables depending on the chosen form of matrix C.

For a description of the regulatory activities of the driver and the implementation of its model in the model system, vehicle - field, shown in figure 1, we started from the concept quasi-linear models of the human operator given in [4], and detailed in [5]. Model driver is presented in the time domain in the form of differential equations of second order,

$$\beta(t) + T_1\dot{\beta}(t) + T_2\ddot{\beta}(t) = \sum_{i=1}^{n} A_i x_i(t - T_i) \tag{7}$$

where, β - turning the steering wheel angle, T_1, T_2 - time constant, as the characteristics of the neuromuscular dynamics of the driver, and A_i - coefficients evaluating information from the driver, T_i - delay the receipt of certain information. In accordance with the physical model, the vehicle - sight field, in figure 1, and the corresponding mathematical models presented by expressions (4), (5), (6) can be specified information to the driver, xi (t - T_i), on the basis of state variables contained in the vector, [x] = [y, y′, ε, ε′], then the variables in the vector output, [z], the variables of the input vector, u = [β, M], and combinations thereof. In this regard, the overall display driver model, given by (7) is reduced to concrete form,

$$\beta(t)+T_1\dot{\beta}(t)+T_2\ddot{\beta}(t)=A_y y(t-T_y)+A_{\dot{y}}\dot{y}(t-T_{\dot{y}})+A_\varepsilon \varepsilon(t-T_\varepsilon)+A_{\dot{\varepsilon}}\dot{\varepsilon}(t-T_{\dot{\varepsilon}}) \quad (8)$$

Using the relation of the vehicle state variables,

$$\ddot{y}=v_x\left(\dot{\varepsilon}+\dot{\alpha}\right) \quad (9)$$

where, d^2y/dt^2 - lateral acceleration of the vehicle, v_x - longitudinal component of the vehicle velocity, dε/dt - angular velocity of turning the vehicle around its vertical axis, dα/dt - angular velocity of swimming vehicles.

It can be the structure of the base model of the driver (8), as a multi-variable controller, converted on the structure model, based on the concept of "vehicle deviation advanced in time". Taking into account the model of the visual field (4), (5) and reducing the neuromuscular dynamics of the driver on the model of the first order, we get the resulting model driver in the equivalent single - input, single - output system as part of a complex simulation - estimation system, shown in figure 2.

$$F_D(s)=\frac{\beta(s)}{y_{ad}(s)}=K\frac{e^{-T_d s}}{1+T_1 s}(1+\frac{L}{v_x}s), \qquad T_a=L/v_x \quad (10)$$

In this case, the time constant, $T_a = L/v_x$, is the quantity ratio of physical variables, the distance of driver sight point, L, and longitudinal components of the vehicle velocity, v_x in the zone extended vehicle dynamics in the visual field, rather than the result generated by predictive control of driver . In this way, its regulatory activity is much easier in the visual field with meaningful visual information, YΔ, for the strategy driving the "single point sight" or YiΔ, i = 1, for the strategy driving the "multi sight points."

With this approach, the formation of driver model in its structure included two state variables, according to the expressions (5), (6). The direct and bearing in mind the relation (9), two state variables indirect, therefore, the total vector of state variables for the adopted model vehicles. This system formed a closed contour, as shown in figure 2 and conducted research in this paper, in a sense, 1) checking the stability of the vehicle in an open contour, 2) study driver behavior in terms of stability of the system in a closed contour, 3) establishment of criteria for assessing the dynamics of vehicles in terms of the required performance and ease of control. In order to display theoretical assumptions as a basis for solving the above-defined segment of the third survey, the establishment of criteria for the evaluation of vehicle dynamics, it is presumed that a well-trained, experienced and motivated driver performs its task in an optimal way in terms of required system performance and minimal fatigue at operation of the vehicle. In this sense, the closed control system, the driver - vehicle - environment, has been expanded with two LQGR1, LQGR2, and controller, connected to the system block diagram as shown in figure 2. In addition, the regulator LQGR1 is placed in parallel to driver control feedback, therefore, can completely replace its effect in some cases research, and its structure is further shown in figure 2, as the primary regulator. The secondary regulator, LQGR2, is set parallel to the subsystem of the steering mechanism - the rear steering wheels and can be alternatively coupled in series with the driver.

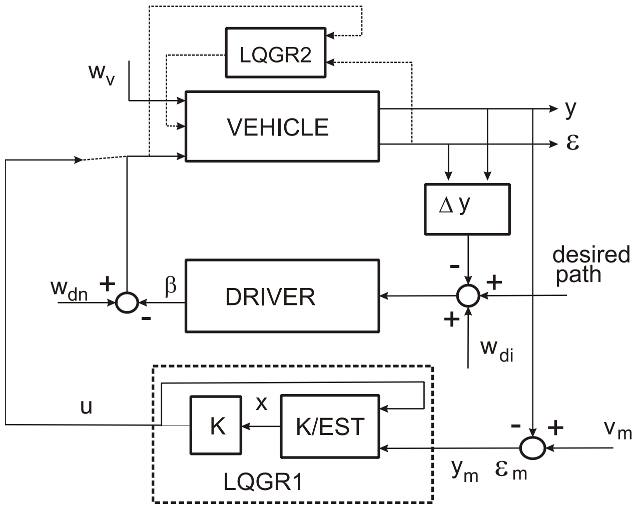


Figure 2 The block diagram of closed loop system, driver – vehicle – sight field - regulators

Design of controllers shown in the block diagram in figure 2, was carried out in two stages. The first phase was chosen concept of optimal control for a given system and set requirements. In the second phase, to define the conditions of implementation of the controller in the system depending on the number of state variables system, their specificity, the difficulty of measurement, measurement errors, the relation between the state variables and inputs, outputs and other impacts in the system and the environment. In this sense, the basis for the effective functioning of the optimal controller K, is the Kalman estimator K / EST, included in this structure, in block LQGR1 on figure 2.

The optimal control concept for both regulators is formulated as a problem to minimize a functional of general form [10]:

$$J = \frac{1}{2} z^T(t_f) S z(t_f) + \frac{1}{2}\int_{t_o}^{t_f}\left[z^T(t)Q(t)z(t) + u^T(t)R(t)u(t)\right]dt \tag{11}$$

where Q, R, S are symmetric weighting matrices, u(t) input, z(t) output variables. With Hamilton – Jacobi equation:

$$H\left[z(t), u(t), \lambda(t), t\right] = \frac{1}{2} z^T Q z + \frac{1}{2} u^T R u + \lambda^T A z + \lambda^T B u \tag{12}$$

and by used maximum principle:

$$\begin{aligned} \frac{\partial H}{\partial u} &= 0 = R(t)u(t) + B^T(t)\lambda(t) \\ \frac{\partial H}{\partial z} &= -\dot{\lambda} = Q(t)z(t) + A^T(t)\lambda(t) \end{aligned} \tag{13}$$

at constraint condition:

$$\lambda(t_f) = \frac{\partial \theta}{\partial z(t_f)} = Sz(t_f) \tag{14}$$

needed solution of (9) is :

$$u(t) = -R^{-1}(t)B^T(t)\lambda(t) \tag{15}$$

with presumed partial solution:

$$\lambda(t) = P(t)z(t) \tag{16}$$

where P(t) is the solution of Riccati matrix equation:

$$\dot{P} = -P(t)A(t) - A^T(t)P(t) + P(t)B(t)R^{-1}(t)B^T(t)P(t) - Q(t) \tag{17}$$

by constraint condition $P(t_f) = S$.

With P(t) solution from equation (17) can be synthesized optimal controller structure in time domain:

$$u(t) = K(t)z(t) = -R^{-1}(t)B^T(t)P(t)z(t) \tag{18}$$

The end result of this mathematical model of the optimal control law (18) carried out the structure and parameters of the block, K in figure 2. The structure and parameters of Kalman estimator, K / EST, determined based on the equation of state Kalman filter are given in the following form,

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + L(\bar{z} - C\hat{x} - Du) \tag{19}$$

With defined of the process noise and the measurement noise covariance data, E (ww^T), E (ww^T) respectively, and the expression (19), was formed in the state space model of Kalman estimator, as follows, as a system with two vector inputs and one output vector,

$$\dot{x} = Ax + Bu + Gu, \qquad \bar{z} = Cx + Du + Hw + v \tag{20}$$

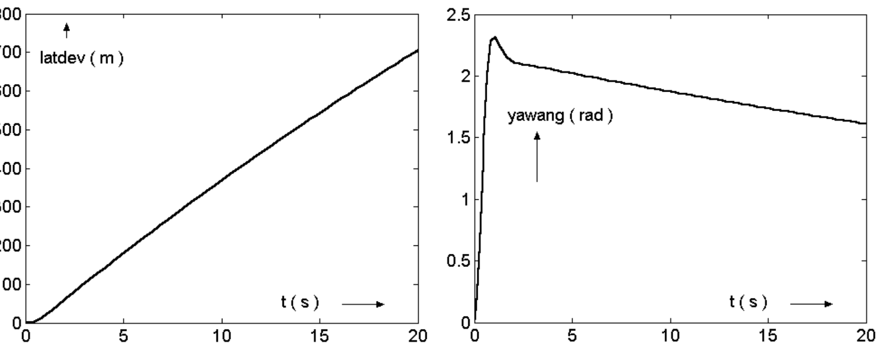
on the basis of determined covariance matrices and estimator gain, obtained as solutions of algebraic Riccati equations, is synthesized the optimal LQG controller, as the coupling of components, K and K / EST, with the state space the equation, 21,

$$\frac{d\hat{x}}{dt} = \left[A - LC - (B - LD)K\right]\hat{x} + L\bar{z}, \quad u = -K\hat{x} \tag{21}$$

In this paper optimization control problem is solved with formed algorithm from equation (6), (10) and from (11) to (18) for defined control task, vehicle and driver. The results of the Riccati matrix equation solutions are used of line in simulation procedure. Real and optimal vehicle control for above in text mentioned research segments are examined on the example a typical passenger car and some results presented in next chapter.

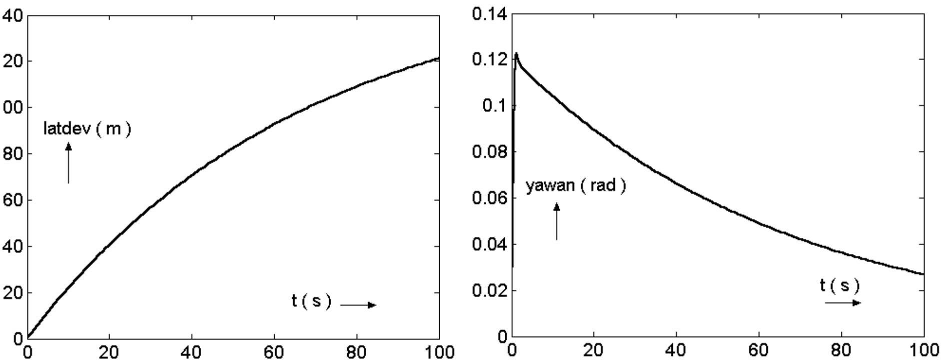
RESEARCH RESULTS

The research results are shown in figures 3 to 10. Figure 3a, b, shows the time history of the vehicle lateral deviation and angular deviation from desired straight line path at constant speed of 70 km/h and by impulse disturbance over front steering wheels. These results illustrate an example of vehicle unstable motion. Namely, after an impulse at zero initial time the vehicle lateral deviation in figure 3a, increases progressively with time. Similar behavior vehicle exhibits by impulse lateral disturbance, in figure 4a, but with different curve slope and settling time of the transient process. Also, the time history of the vehicle state variables, presented in figure 3, 4, can be used as indicators of vehicle instability in time domain. The equivalents of these indicators in frequency domain are roots of vehicle system matrix A, (6), presented in figure 5a, as poles chart. The real part of each pole is an indicator of vehicle (un)stability , depending of sign (+) - , respectively, while the imaginary part indicates oscillating behavior of the vehicle state variable.



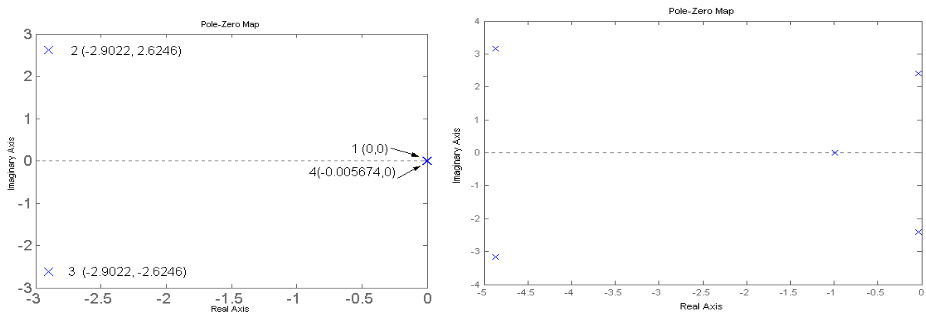
a) *b)*

Figure 3 The time history of the vehicle lateral, a), and angular deviation, b), from desired path during impulse excitation over the steering wheel and vehicle speed of 70 km/h



a) *b)*

Figure 4 The time history of the vehicle lateral deviation a) and angular deviation b), from desired path during lateral impulse excitation and vehicle speed of 70 km/h. a/Δy, b Δε , (according to figure 1)



a) b)

Figure 5 Poles chart of a) vehicle lateral dynamics model, b) system driver – vehicle – sight field model

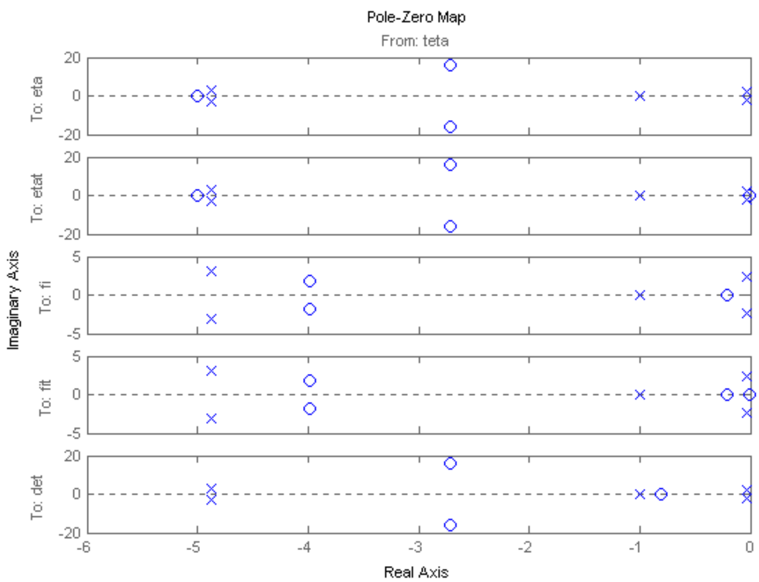


Figure 6 Pole – Zero Map for system driver – vehicle – sight field with five state variables, marked for top to bottom: y, dy/dt, ε, dε/dt, β, respectively, according to figure 1

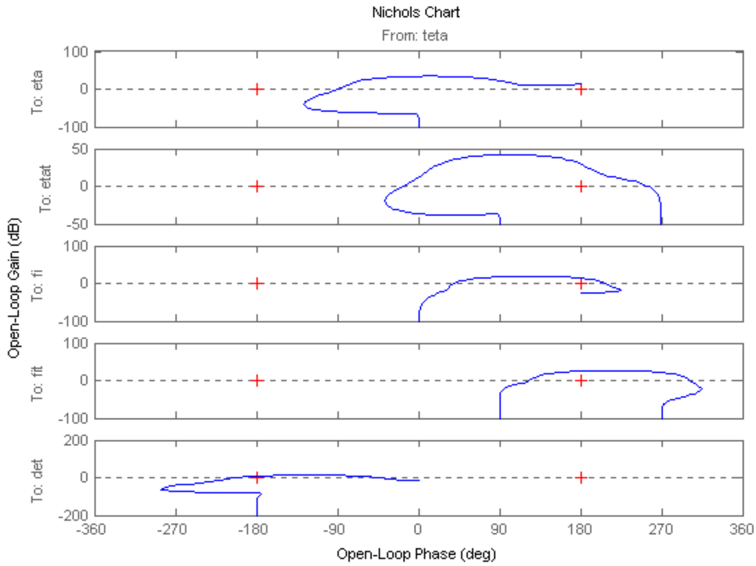


Figure 7 System open –loop gain versa open-loop phase, input ΔY, from (5), output, for top to bottom: y, dy/dt, ε, dε/dt, β, respectively, according to figure 1

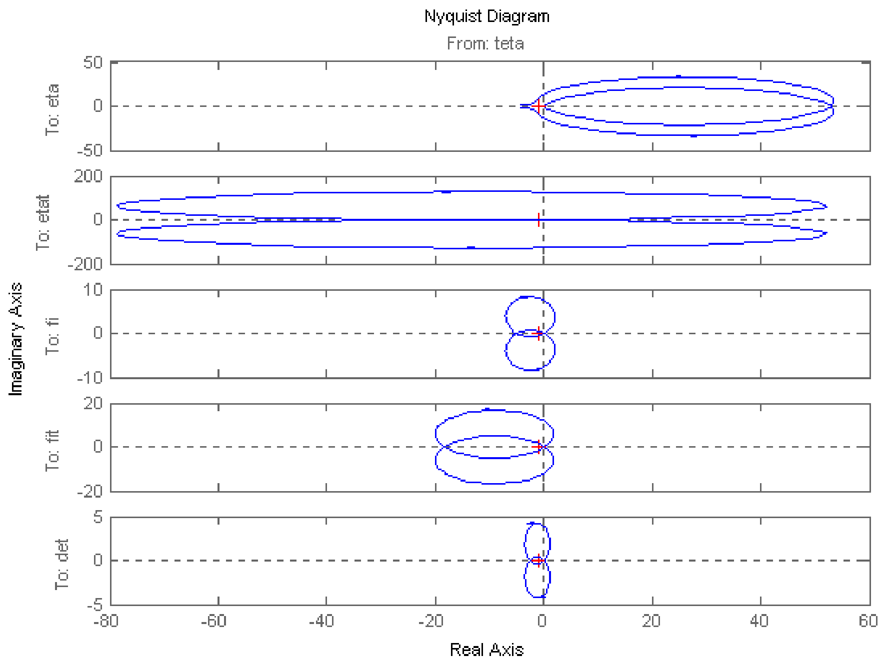


Figure 8 System polar plots, input ΔY, from (5), output, for top to bottom: y, dy/dt, ε, dε/dt, β, respectively, according to figure 1

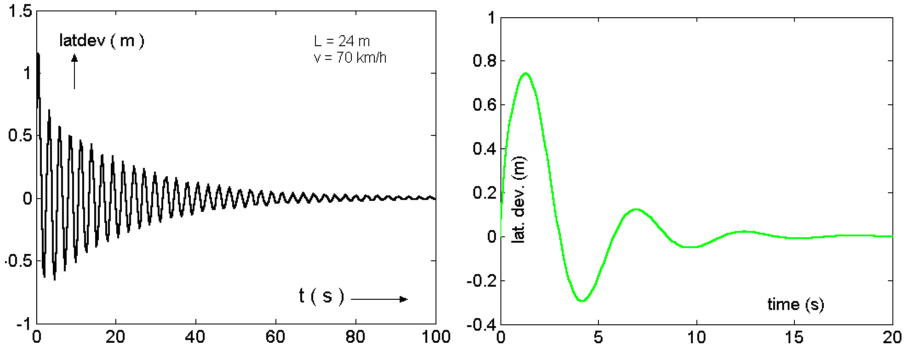


Figure 9 The time history of the vehicle lateral deviation from desired path during lateral impulse excitation of, a) 5m/s, b) 2 m/s, at longitudinal vehicle speed of 70 km/h and distance of driver sight point of 24 m

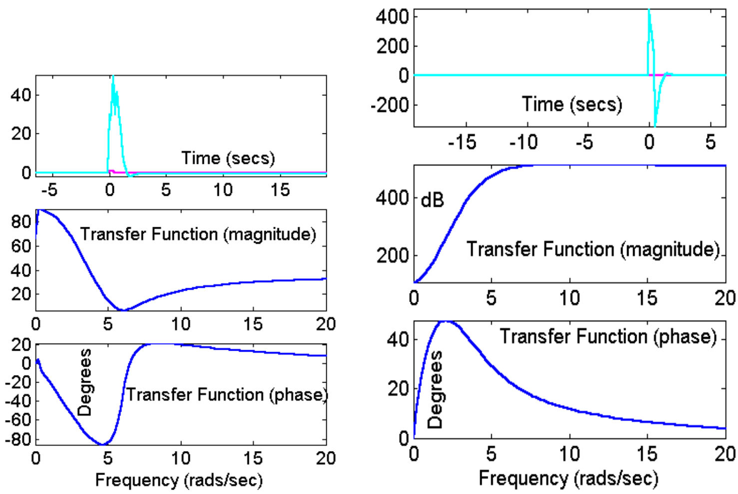


Figure 10 Vehicle transfer function , a) input steering wheel angle, output lateral acceleration, b) input steering wheel angle, output, advanced lateral deviation, for sight point distance of 24m

The pole locations in figure 5a indicate two critical poles, marked with numbers 1 and 4, which are caused unstable motion according to figure 3 and 4.

The results in figure 5b, shown that driver control action improve system performance with respect to stability. The system, driver – vehicle sight field has now five poles, also, one more than vehicle subsystem in open loop, and all poles have negative real parts what indicate stable motion. This fact confirm results in figure 9, presented as time history of the vehicle lateral deviation from desired straight line path at two levels lateral impulse disturbance, a) 5m/s, b) 2m/s, longitudinal speed of 70 km/h, sight point distance of 24 m and by optimal set of driver model parameters, (10). In this case, the change of the vehicle lateral deviation indicates the transient, well damped, stable process, whose parameters depend of the lateral disturbance intensity.

On the basis obtained system pole – zero distribution, in figure 6, are formed typical indicators of system behavior in frequency domain shown in figure 7, as system open loop gain versa open loop phase, so-called Nichols chart and in figure 7, as polar diagram with coordinates: complex transfer function as vector versa phase angle as scalar and circular frequency as parameter, also, presentation so – called Nyquist diagram. These graphs shown five typical modes of system transfer function according to chosen vehicle state variables, vector [x] in model (6), plus added state variable of steering wheel angle, and defined input of » advanced vehicle deviation«. With graphs presented in figure 7 and 8, are functional connected graphs shown in figure 10, as relation magnitude and phase of circular frequency.

The further improvement of the system performance can be achieved by using implemented LQG regulator, according to block diagram in figure 2, and given algorithm, from (11) to (21). But in this paper, the role of the optimal regulator is used for the development of assessment criteria of vehicle dynamics. In this sense, according to a given algorithm are identified the optimal control laws and thus demands that the dynamics of the vehicle sets to driver as a regulator. As an illustrative example are shown the results of this segment of the research for the two speeds of the vehicle, of 70 and 90 km/h and a full format of the vehicle state variables in the open loop, according to equation (18), as follows,

$$
\begin{aligned}
u(t) &= K * z(t) = 0.7071y + 0.5938\dot{y} + 3.5095\varepsilon + 0.4285\dot{\varepsilon}, \qquad at \quad 70km/h \\
u(t) &= K * z(t) = 0.7071y + 0.6202\dot{y} + 3.9077\varepsilon + 0.4278\dot{\varepsilon}, \qquad at \quad 90km/h
\end{aligned}
\tag{22}
$$

The gain factors identified in the expressions (22) indicate rank the importance of input variables of the optimal regulator. The vehicle speed shows the influence of the factors gain Ky' and $K\varepsilon$, so, on the speed of lateral movement of vehicles and vehicle turning angle around the vertical axis. Comparing equation (22) with (8) it can be concluded that the obtained gain factors are the good basis to evaluating information for model drivers, therefore the impact of vehicle dynamics on control activity driver.

CONCLUSIONS

For its structural properties and dynamic characteristics of the motor vehicle wheel does not have its own stability of direction in relation to location coordinates. To stabilize the vehicle driver must use visual information from the visual field and mechanical information from interaction system and environment based on them express adequately the effect of the command driving. At the same time, the driver of his action suits a movement and vehicle dynamics which makes a certain degree tiring. A well-trained, experienced and motivated driver acts optimally on command vehicles in terms of demand system performance and ease of management. Therefore, the rational use of available information from the visual field and system interactions, stabilize the movement of the vehicle along with its minimal deviation from the desired trajectory in terms of demands for safe movement and minimal fatigue. According to the results obtained in this paper, the design and implementation of optimal controllers in the vehicle structure, enabled the stabilization of the system, improve the controllability, establishing criteria for assessing the quality of the vehicle in terms of its behavior on the road, the effect on his team and the effect of external influence.

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