EVALUATION OF THE CORRECTNESS OF PERFORMANCE OF TYPICAL VEHICLE DRIVE MANOEUVRES vs. STEERING EFFORT

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Abstract

The paper concerns the modelling of lateral dynamics of vehicle movement. Two concepts related to vehicle steering were presented and compared with each other in this paper. One of them was related to the idea of a curvilinear motion assistance system, which might be used for automatic vehicle driving or for the correction of driver's actions. It aimed at the optimization of the steering wheel input in terms of the correctness of performance of typical manoeuvres.

The other one was related to the realization of steering assistance. It concerned the evaluation of steering control quality by determination of the steering effort value. For the analysis of the correctness of typical manoeuvres performance, a double lane-change manoeuvre was chosen. To evaluate the correct performance of the manoeuvre an objective function was adopted and presented in the paper.

A computer simulation of two examples of the typical double lane-change manoeuvre was carried out. The first example concerned an avoidance of an obstacle having suddenly sprung up and the second one concerned an avoidance of an obstacle without the element of surprise. Some examples of computer simulation results were presented and discussed in the paper.

Keywords: *objective function, correct execution of a manoeuvre, steering effort, steering control quality evaluation, simulation of a manoeuvre*

1. Introduction

For quite a long time, efforts are made (without neglecting any actions that might help to improve drivers' skill and sense of responsibility) for vehicle characteristics to be so designed and for the vehicle to be provided with such devices and auxiliary systems that, in spite of imperfections of senses and personality traits of the human driver, the vehicle should ensure the highest level of drive safety. Simply it can be said that we are striving to make the vehicle compensate for driver's faults and deficiencies.

To pursue this objective, a variety of systems are being introduced as driving aids, which are then gradually developed and combined together into systems of higher levels of integration. In consequence, a concept of "assistance systems" has appeared and it has recently begun to predominate in publications concerning new concepts of development of automotive vehicles, e.g. [1], [4], [8], [10], [13], or [21].

Simultaneously, when various driving aids were introduced, it turned out that a matter of particular importance is to ensure the steering of a driven vehicle to be “favourably” felt by the driver [9]. According to the authors of papers [2] and [3], the giving of this favourable feel and more pleasure to the driver is a sort of challenge for the manufacturers of modern vehicles and it may improve the vehicle steering control quality as well. The observed growing importance of the vehicle steering feel is also connected with the plans to introduce the “steer-by-wire” [3] systems to vehicles. Moreover, this may pave the way in the future for the tuning of the steering system of a specific vehicle for individual driver’s needs and traits.

For the evaluation of steering systems, the authors of papers [2] and [3] have proposed to use the concept of “steering effort,” with the meaning of this term being different than that of the “driver’s effort” understood as the work done by the driver when turning the steering wheel. While the definitions of the term “steering effort” that can be found in the publications available have been discussed in papers [2] and [3], the authors of those papers have proposed to introduce a complex concept of “steering effort” presented in paper [7], where not only the steering torque but also the steering wheel angle and lateral acceleration values have been taken into account. Experiments have confirmed strong correlation to exist between the steering effort defined as above and the subjective rating of steering control quality [7]. It has been shown [11, 12] that changes in steering torque, steering wheel angle, and lateral acceleration are distinctly felt by the driver and affect his/her steering feel.

The development of simulation tests has offered new research opportunities making it possible to get to know various processes and phenomena that influence the vehicle’s behaviour in various road conditions, even extremely unfavourable, with driver’s actions or feelings being also taken into account.

This paper refers to the idea of assistance in the performance of curvilinear motion according to which the steering control system should “perceive” (“see”) the manoeuvre as a whole. Based on the idea of assistance in the performance of curvilinear motion and with the use of the objective function as a measure of the correct performance of a manoeuvre, a computer simulation of the execution of typical manoeuvres was carried out. Simultaneously, the steering effort as defined in [2] and [3] was determined for the same test runs to complement the idea of assistance in the performance of curvilinear motion. Then, the results obtained were discussed.

2. Criteria of correct performance of a manoeuvre

The issue of correct performance of a manoeuvre has been discussed in details in [17] as well as in [15]. Therefore, only a brief reference will be made here to this subject matter.

For a manoeuvre to be assessed as correctly performed road feel and ride comfort as well as adequate safety should be ensured and, simultaneously, no excessive loads should develop in the vehicle steering system.

To evaluate the correct performance of a manoeuvre, the following criteria may be adopted:

a) Precision of the following of the predicted vehicle course: remaining within the prescribed corridor;
b) Smooth steering: avoiding of rapid, frequent movements of the steering wheel;
c) Passengers’ feeling of ride comfort.

For the above criteria to be quantified, appropriate measurable physical quantities should be adopted. So, the following have been chosen as the corresponding measures [14]:

1) The precision of the following of the predicted course by a vehicle is measured by the minimum distance from the vehicle body to the edge of the lane as recorded during the manoeuvre, on the condition that the vehicle should remain within the prescribed corridor.
2) To evaluate the smoothness of steering, the angular speed of the steering wheel is used.
3) Passengers’ ride comfort is evaluated on the grounds of the maximum lateral acceleration value a_{ymax} that occurred during the manoeuvre.

To measure the correctness of performance of a manoeuvre, an objective function in the following form has been adopted [14]:

$$J_W = w_1 \frac{1}{T}\int_0^T \dot{\delta}_H^{\,2}\, dt + w_2 \cdot \kappa_{max}^2 + w_3 a_{y\,max}^2 , \tag{1}$$

where:
$\dot{\delta}_H$ - time derivative of the steering wheel angle,
T - time of the test run,
$\kappa = \frac{1}{\varepsilon}$ - inverse of the distance from the edge of the traffic lane,
a_{ymax} - maximum lateral acceleration,
w_1, w_2, w_3 - weights.

The optimization of the steering wheel input at the execution of road manoeuvres with the use of sequences of specific movements of the steering wheel has been explained in details in papers [14], [15], [16], [17], [18], [19], and [20]. At this method, the optimum test runs are determined, composed of fragments of the sinus function of specific amplitudes (A) and frequencies (f) and optimized according to the functional assumed (1). The optimization criterion is defined by the functional (1), which favours the maximum precision of the following of the predicted vehicle course, smooth steering (smooth movements of the steering wheel, with no jerks), and passengers' feeling of ride comfort. For a specific manoeuvre, the optimization is based on simulation runs where the minimum of the functional (1) is searched at every successive step. The weight values vs. the vehicle speed are given in Table 1 [14].

Tab. 1. Weights w_1, w_2, and w_3 vs. the vehicle speed [14]

Vehicle speed km/h (m/s)	Weight w_1 s^2/rad^2	Weight w_2 $1/m^2$	Weight w_3 s^4/m^2
40 (11.11)	0.80	1.0	0.30
60 (16.67)	0.80	1.0	0.40
80 (22.22)	0.80	1.0	0.50
100 (27.78)	0.80	1.0	0.75
120 (33.33)	0.80	1.0	1.00

3. Steering effort

In papers [2] and [3], the authors have defined the concept of "steering effort" and discussed its values. According to their opinion, it seems reasonable to associate the steering effort with the lateral acceleration of the vehicle. Such an approach has been presented in paper [7] and the steering effort has been defined there as the product of the steering wheel angle gradient $d\delta_H/da_y$ and the steering wheel torque gradient dM_H/da_y with respect to the lateral acceleration a_y [7].

$$E' = \frac{d\delta_H}{da_y} \cdot \frac{dM_H}{da_y} , \tag{2}$$

where:
a_y - standardized lateral acceleration divided by standard gravity[2].

The author of paper [7] has determined the optimum value of the steering effort (E'_{opt}) (2) as 5250 deg*Nm. Based on this value and experimental tests carried out, a range of the steering effort values considered favourable has been determined as $1/5 \cdot E'_{opt}$ - $5 \cdot E'_{opt}$.

The concept of steering effort defined as above, with the above favourable range of the steering effort values, may be used to evaluate steering systems.

The authors of papers [2] and [3] took on this task and carried out experimental tests; then, based on the test results, they discussed the possibility to use the steering effort concept for the evaluation of steering control quality. They have shown the usability of their idea for the studying of the problem of ensuring the driver a favourable steering feel.

In this paper, the authors analyze the dependence of the steering effort on the optimisation of the input applied to the steering wheel when performing a road manoeuvre.

4. Formulation of the test task

A computer simulation of two examples of the typical double lane-change manoeuvre has been carried out:

1 – "Avoidance of an obstacle having suddenly sprung up" based on [5], Fig. 1;

2 – "Avoidance of an obstacle without the element of surprise" based on [6], Fig. 2.

The task was to select the values of the steering wheel input parameters (amplitude A and frequency f) so that the manoeuvre would be correctly performed with simultaneous minimization of the objective function J_W (1). Thus, the values of parameters A and f were determined, at which the objective function J_W reached its minimum. Then, a few manoeuvre simulation tests were carried out for other values of parameters A and f so selected that the manoeuvre performance could be evaluated as correct (in terms of criterion (1)) and various values of J_W were obtained.

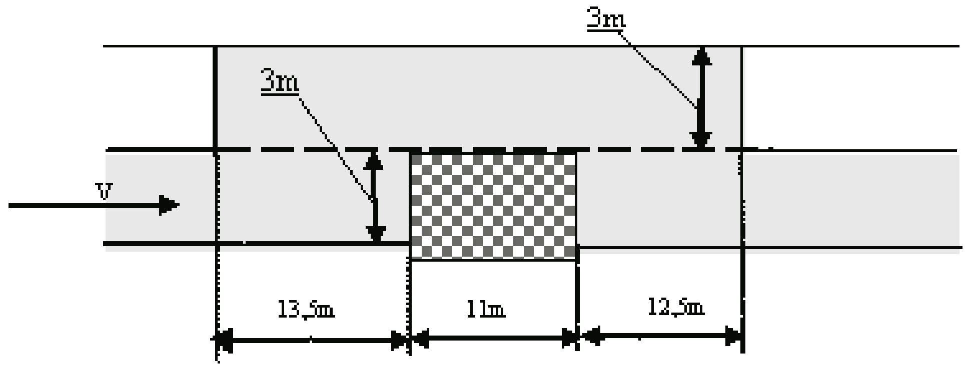

Fig. 1. Corridor for the manoeuvre "avoidance of an obstacle having suddenly sprung up"

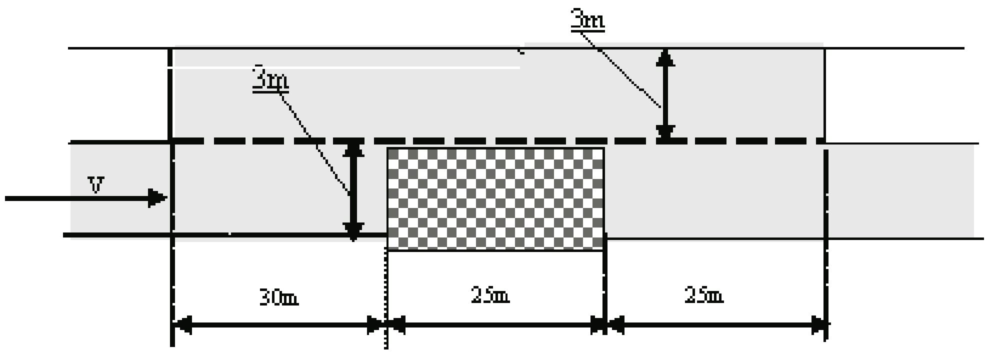

Fig. 2. Corridor for the manoeuvre "avoidance of an obstacle without the element of surprise"

The task as above was carried out for the manoeuvres "avoidance of an obstacle having suddenly sprung up" and "avoidance of an obstacle without the element of surprise." Then, the steering effort E' was determined in accordance with formula (2) for the same test runs.

5. Analysis of results

The values of the objective function J_W (1), steering wheel input parameters A and f, terms being factors in equation (2), and steering effort E' determined for the manoeuvres as described above are given in Tables 2 and 3.

Tab. 2. Values for the manoeuvre "avoidance of an obstacle having suddenly sprung up"

No.	J_W	A [rad]	f [rad/s]	$\frac{d\delta_H}{da_y}$ [deg]	$\frac{dM_H}{da_y}$ [Nm]	$E' = \frac{d\delta_H}{da_y} \cdot \frac{dM_H}{da_y}$ [deg*Nm]
1	41.50	0.65	1.75	256.57	10.99	2819
2	10.90	0.80	1.90	254.99	11.09	2827
3	7.77	0.95	2.05	254.94	11.18	2851
4*)	**7.30**	**1.10**	**2.20**	**259.23**	**12.65**	**3280**
5	8.37	1.25	2.35	262.06	12.56	3291
6	10.51	1.40	2.50	265.16	13.24	3512
7	13.67	1.55	2.65	272.75	14.03	3826
8	17.31	1.70	2.80	275.55	14.42	3974
9	22.11	1.85	2.95	280.62	14.32	4019
10	28.58	2.00	3.10	281.38	14.52	4085
11	37.85	2.15	3.25	284.75	15.30	4358

*) *The least value of the objective function (1)*

Furthermore, the trajectories of a vehicle performing the manoeuvres at three typical runs, i.e. at the lowest value of the steering effort E' (2), denoted as "E'min"; at the lowest value of the objective function J_W (1), denoted as "$J_W$min"; and at the highest value of the steering effort E' (2), denoted as "E'max," are shown in Figs. 3 and 4.

Tab. 3. Values for the manoeuvre "avoidance of an obstacle without the element of surprise"

No.	J_W	A [rad]	f [rad/s]	$\frac{d\delta_H}{da_y}$ [deg]	$\frac{dM_H}{da_y}$ [Nm]	$E' = \frac{d\delta_H}{da_y} \cdot \frac{dM_H}{da_y}$ [deg*Nm]
1	17.449	0.28	1.18	269.78	9.91	2673
2	8.848	0.30	1.20	266.84	10.50	2801
3	73.17	0.30	1.25	265.88	10.59	2817
4	19.545	0.35	1.20	266.51	10.59	2824
5	4.459	0.40	1.35	261.74	10.99	2876
6*)	**4.444**	**0.35**	**1.25**	**266.55**	**10.79**	**2876**
7	6.29	0.45	1.40	282.01	10.30	2905
8	9.828	0.35	1.30	268.77	10.99	2953
9	10.408	0.40	1.30	268.99	11.09	2982
10	32.634	0.45	1.35	276.06	10.89	3006
11	87.981	0.48	1.38	267.98	11.38	3049

*) *The least value of the objective function (1)*

The results, presented show that the lowest values of the steering effort E', occur at the manoeuvres performed "gently," i.e. at the lowest values of amplitude A and frequency f of the steering wheel input. Along with an increase of the A and f values, the steering effort values grow as well. The optimum runs, selected according to the functional assumed (1), have also been marked in Tables 2 and 3. The values of the simulation test results presented in Tables 2 and 3 show that the criterion of minimum steering effort E' causes the system to try to perform the manoeuvre at the lowest possible work, i.e. at the lowest values of parameters A and f, even at the cost of reduced distance from the right-hand edge of the traffic lane (see Figs. 3 and 4). The highest E' values occur at the manoeuvres performed at the highest values of the parameters A and f. At the manoeuvre "avoidance of an obstacle having suddenly sprung up," the decisive factor is the frequency f of the steering wheel input, corresponding to rapid growth of lateral displacement, with the maximum trajectory deviation being close to that observed at E'min (Fig. 3).

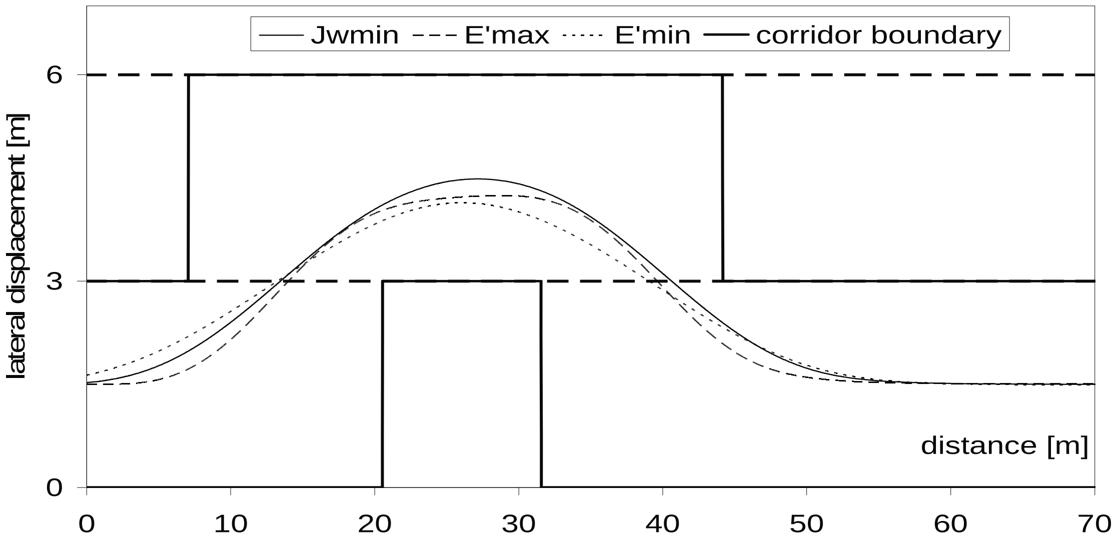

Fig. 3. Vehicle trajectory at the manoeuvre "avoidance of an obstacle having suddenly sprung up"

At the manoeuvre "avoidance of an obstacle without the element of surprise," the decisive role seems to be played by the influence of the amplitude A, which corresponds to gentle growth of lateral displacement and significant trajectory deviation outward of the traffic lane (Fig. 4). If, however, the criterion of J_W (1) is taken as a basis, the system "optimizes" the manoeuvre by making use of the full available width of the traffic lane, trying to keep the vehicle at an "approximately equal" distance from both edges of the traffic lane.

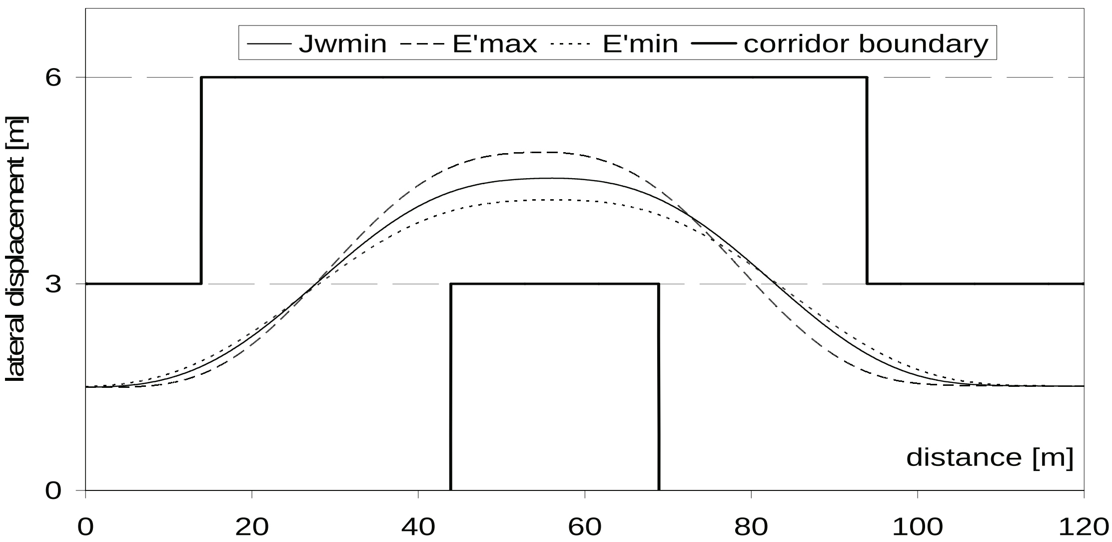

Fig. 4. Vehicle trajectory at the manoeuvre "avoidance of an obstacle without the element of surprise"

The distribution ranges of the values of steering effort E' and its constituent factors $\frac{dM_H}{da_y}$ and $\frac{d\delta_H}{da_y}$ vs. the steering wheel input parameters A and f, determined for both manoeuvres under consideration, are presented in Figs. 5 through 10, with the trend lines being also shown to visualize the character of the data distribution. Based on an analysis of these curves, we may state as follows: at the manoeuvre "avoidance of an obstacle having suddenly sprung up," the values of the factors $\frac{dM_H}{da_y}$ and $\frac{d\delta_H}{da_y}$ (and the value of E' (2), in consequence) are more strongly affected by the frequency f than by the amplitude A of the steering wheel input, which is visualized by the steeper angles of inclination of the trend lines in the graphs denoted with b) as against those of the corresponding graphs a), according to the observation made earlier, i.e. when the vehicle trajectory was analyzed.

At the manoeuvre "avoidance of an obstacle without the element of surprise," the frequency f and amplitude A of the steering wheel input have similar influence on the values of the factors $\frac{dM_H}{da_y}$ and $\frac{d\delta_H}{da_y}$ (and on the value of E' (2), in consequence), as it can be seen from the similar angles of inclination of the trend lines in the graph pairs denoted with a) and b), which was again noticed earlier, i.e. when the vehicle trajectory was analyzed.

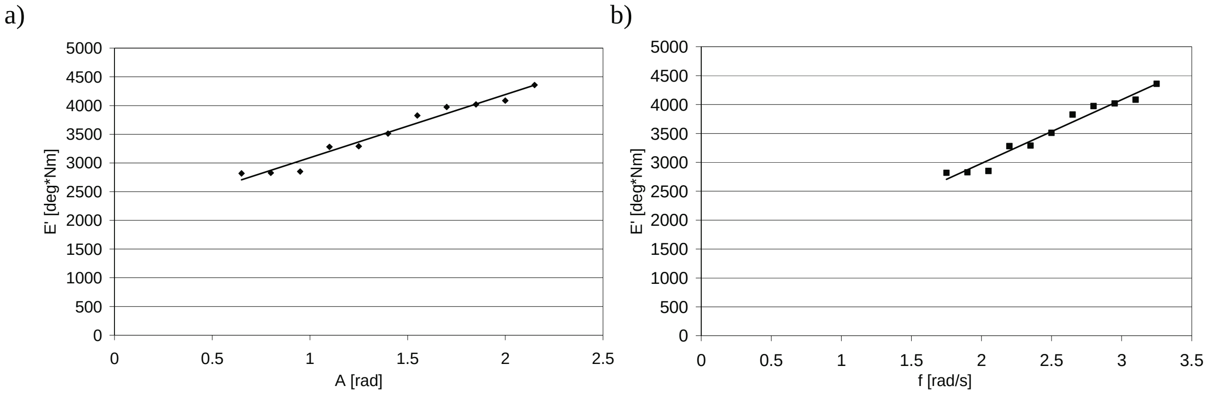

Fig. 5. "Avoidance of an obstacle having suddenly sprung up." Range of values of the steering effort E' depending on: a) steering wheel input amplitude A; b) steering input frequency f

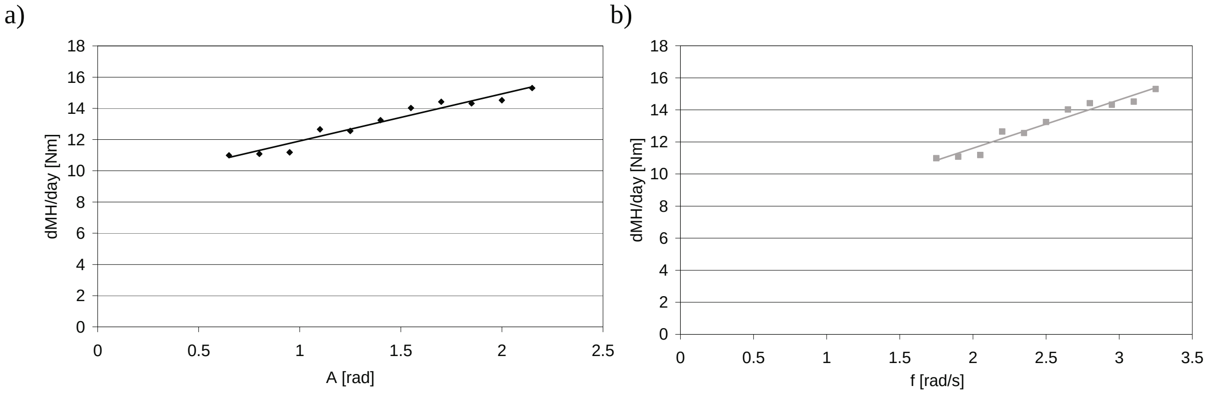

Fig. 6. "Avoidance of an obstacle having suddenly sprung up." Range of values of the factor $\frac{dM_H}{da_y}$ *depending on: a) Steering wheel input amplitude A; b) Steering input frequency f*

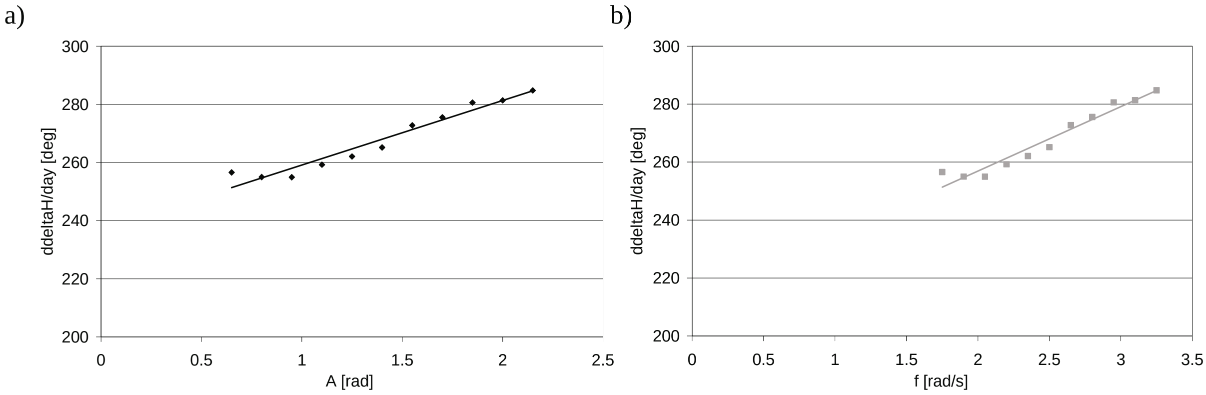

Fig. 7. "Avoidance of an obstacle having suddenly sprung up." Range of values of the factor $\frac{d\delta_H}{da_y}$ *depending on: a) Steering wheel input amplitude A; b) Steering input frequency f*

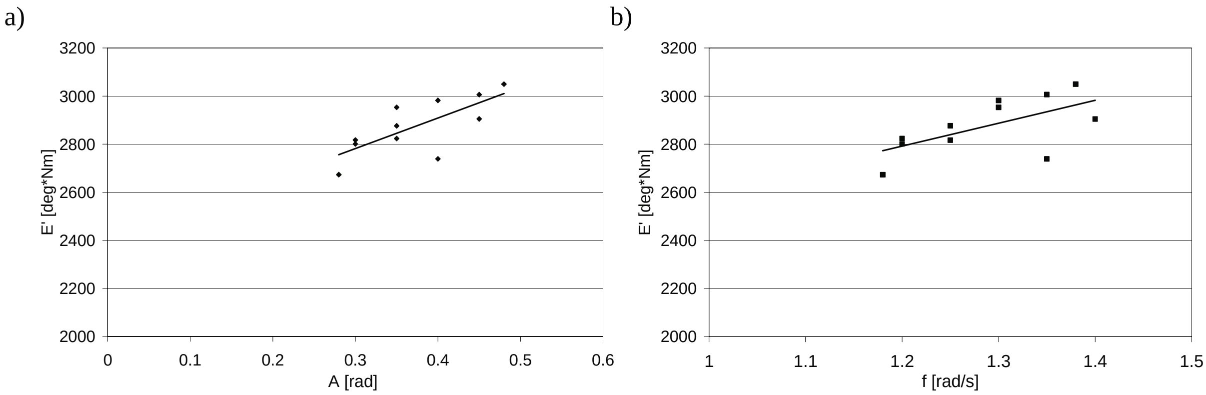

Fig. 8. "Avoidance of an obstacle without the element of surprise." Range of values of the steering effort E' depending on: a) Steering wheel input amplitude A; b) Steering input frequency f

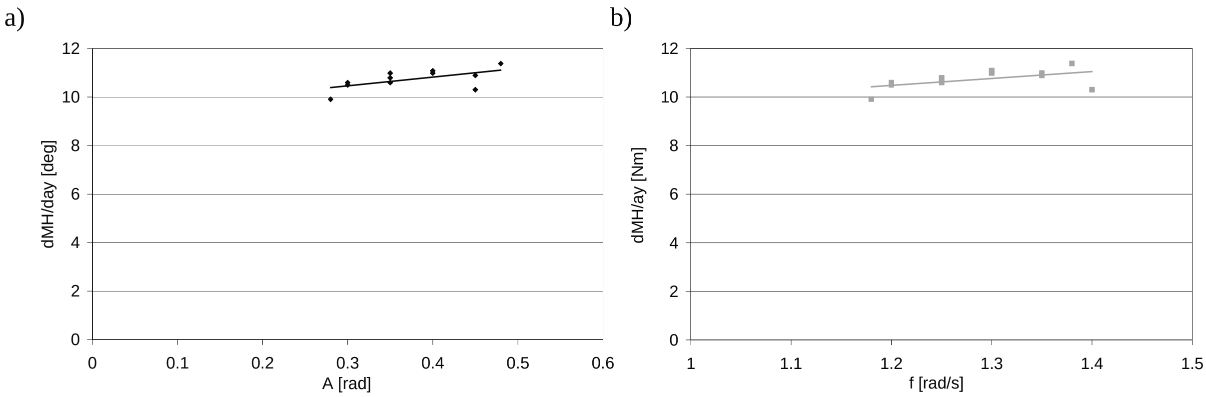

Fig. 9. "Avoidance of an obstacle without the element of surprise." Range of values of the factor $\frac{dM_H}{da_y}$ *depending on: a) Steering wheel input amplitude A; b) Steering input frequency f*

This may be explained by the fact that for manoeuvres performed suddenly, "rapidly," or "out of surprise," stronger influence on the steering effort value is exerted by the steering wheel turning speed (represented by the input frequency f) than by the input amplitude A. In the case that the manoeuvre is carried out with no element of surprise or "gently," the influence of input frequency and input amplitude on the E' value is approximately equal to each other.

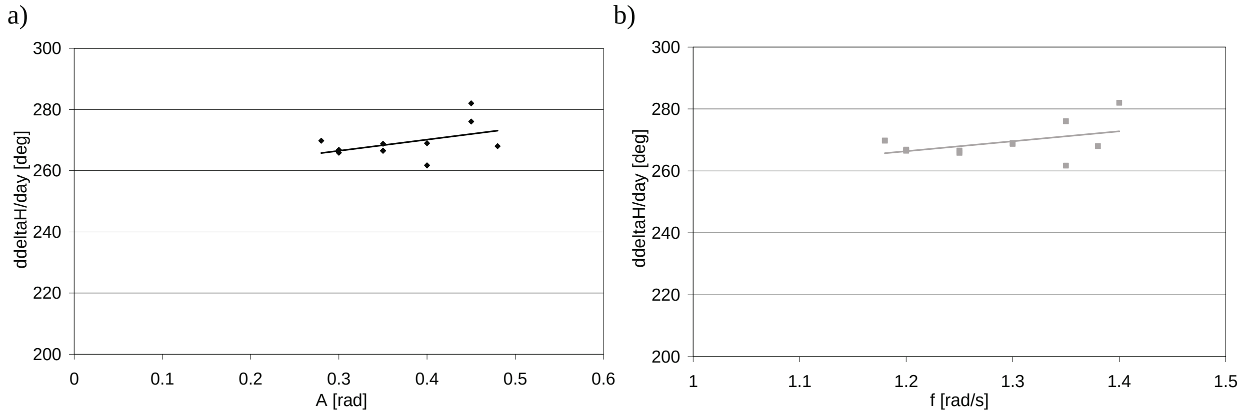

Fig. 10. "Avoidance of an obstacle without the element of surprise." Range of values of the factor $\frac{d\delta_H}{da_y}$ *depending on: a) Steering wheel input amplitude A; b) Steering input frequency f*

6. Conclusions

Two concepts related to vehicle steering have been presented and compared with each other in this paper.

One of them is aimed at the optimization of the steering wheel input in terms of the correctness of performance of typical manoeuvres. It is related to the idea of a curvilinear motion assistance system, which might be used for automatic vehicle driving or for the correction of driver's actions.

The other one concerns the evaluation of steering control quality by determination of the steering effort value and is related to the realization of steering assistance.

Based on an analysis of the computer simulation tests covering both of these concepts, the following conclusions may be proposed.

1. The relatively simple form of the objective function as proposed in this paper may be used for quick and good evaluation of the correctness of manoeuvre execution and for the realization of the idea of assistance in the performance of curvilinear motion at specific manoeuvres.
2. The steering effort may be used for the evaluation of a steering system. The steering effort value obtained from a test enables quick and easy assessment of the steering system of a specific vehicle.
3. The lowest steering effort values occur at manoeuvres carried out "gently," i.e. at the lowest values of steering wheel input amplitudes and frequencies. At increasing values of these parameters of the steering wheel input, the steering effort values grow as well.
4. The application of the criterion of minimum steering effort causes the system to try to perform a manoeuvre at the minimum work, i.e. at the lowest possible values of the steering wheel input parameters (amplitude and frequency), even at the cost of reduced distance from the right-hand edge of the traffic lane. On the other hand, if the optimization criterion related to the correctness of performance of a manoeuvre is taken as a basis, the system tries to make use of the full available width of the traffic lane and to keep the vehicle at an "approximately equal" distance from both edges of the lane.
5. It has been observed that for manoeuvres performed suddenly or "rapidly," stronger influence on the steering effort value is exerted by the steering wheel turning speed (represented by the input frequency) than by the input amplitude. In the case, that the manoeuvre is carried out with no element of surprise or "gently," the influence of input frequency and input amplitude on the steering effort value is approximately equal to each other.

6. For manoeuvres performed suddenly or "rapidly," the values of the gradient $\frac{dM_H}{da_y}$ are higher as against those determined for manoeuvres carried out "gently."

The results of the simulation tests confirm the advisability of studying these issues. It seems reasonable to continue the research work of this type, with simultaneous expanding the work scope e.g. to other manoeuvres or to the investigation of the influence of the dynamics of the steering system on the execution of manoeuvres.

The general findings presented in the conclusions should be verified by a larger number of measurements.

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