Parameters for the Characterization of Motor Vehicle Acceleration Ability

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Abstract – For the characterization of vehicle acceleration, in addition to such common parameters as change of speed and acceleration in time, there should be applied one more parameter: change of acceleration increase in time. Change of acceleration increase in time \( j_p \) progresses in four specific phases in each gear: I – beginning of run where \( j_p \) is growing rapidly to the maximum value of the gear; II – \( j_p \) reduction from the maximum value to the stabilized value; III – speeding up with stabilized value \( j_p \) and IV – shifting when \( j_p \) value is changing in a wide range to the maximum negative value and then to zero.

Keywords – Acceleration of vehicles, increase of acceleration, jars.

I. INTRODUCTION

As it is known, acceleration ability is a parameter for the dynamism of vehicle run up: reaching high speed during a short period of time [1], [2].

The dynamism of vehicle speeding up and, accordingly, acceleration ability are commonly characterized by:
- run up acceleration \( a \);
- run up maximum value \( a_{\text{max}} \);
- speeding up time \( t_{\text{ie}} \);
- distance \( s_{\text{ie}} \) for reaching certain speed \( v \), for example, 100 km/h;
- distance for covering a certain distance, for example, 400 m or 1000 m;
- distance change \( s_{\text{ie}} \) in time \( t_{\text{ie}} \) [1], [3]–[11].

There is one more parameter used for dynamism – acceleration factor \( \eta_j \). This is a ratio between power of inertia resistance overcoming \( N_j \) and power of potential traction supplied for driving \( N_k \) (1) [1]:

\[
\eta_j = \frac{N_j}{N_k} .
\]

The definition and calculations of those parameters is a task of Theory of Ground Vehicles science sector [4], [12], [13] and particularly of its branches – Theory of Automobile [1]–[3], [5]–[7], [14], [15] and Theory of Motorcycle [9].

For instance, acceleration \( a \) of vehicles depending on powers applied to vehicles, namely traction power \( P_k \) and all \( i \) resistance powers \( P_i \) influencing vehicles in particular drive conditions, and reduced mass of vehicles \( m_{\text{red}} \), can be defined as (2) [1]:

\[
a = \frac{dv}{dt_{\text{ie}}} = \frac{P_k - \sum P_i}{m_{\text{red}}} .
\]

Analysis and calculations are easier if the dynamic factor of vehicles \( D \), road-resistance ratio \( \psi \) and coefficient of vehicle gyrating masses \( \delta \) are known (3) [1]:

\[
a = \frac{\delta}{\delta}(D - \psi) .
\]

The maximum value of acceleration \( a_{\text{max}} \) can be found from the same formula (3) if dynamic factor \( D \) in it is replaced by its maximum value \( D_{\text{max}} \) for particular conditions of vehicle operation.

If the adhesion of vehicle movers with the ground surface is limited, acceleration values including the maximum one can be found from formula (3), replacing \( D \) with meshing dynamic factor \( D_\phi \).
When acceleration values are known, speeding up time $t_{ie}$ and starting distance $s_{ie}$ values can be determined, in particular for speed changes from $v_1$ to $v_2$ (4), (5) [1], [4], [7]:

$$t_{ie} = \int_{v_1}^{v_2} \frac{dv}{a}$$

(4)

and

$$s_{ie} = \int_{v_1}^{v_2} \frac{v}{a} dv .$$

(5)

Usually, the above mentioned parameters are sufficient for conventional vehicles with normal dynamism. However, nowadays when acceleration of dynamic vehicles is already characterized by 4 to 5 seconds or even less for reaching a speed of 100 km/h (see Table I), these parameters become insufficient [16]–[19].

In such cases, one of the most important parameters alongside the developed acceleration is an increase of its speed $\frac{da}{dt}$, namely the parameter which characterizes how fast acceleration can be or has been increased. Therefore, it is now necessary to add to the traditional acceleration ability parameters one more parameter – speed of acceleration gain $j_p$, measured in m/s$^3$. Analogue parameter oscillation in theory is called jar or jerk by some mechanics. In this article, we will abstain from searching any other names and, therefore, use term jars.

II. SUPPLEMENT TO THE PARAMETERS OF ACCELERATION ABILITY

Analytical and graph-analytical methods will be used in this article for clearing up the acceleration ability.

| Automobile | Engine power, hp | Engine torque, N·m | $t_{ie}, s/(100$ km/h) |
|------------|------------------|--------------------|---------------------|
| Mercedes CL 500 Blue Efficiency | 435 | 530 | 4.9 |
| BMW 7 ActiveHybrid | 465 | 700 | 4.9 |
| Lansarea CL600 with V12 turbo 5.5 l engine | 517 | 830 | 4.6 |
| AUDI SLS AMG E-CELL with V8 6.3 l engine | 532 | 880 | 4.0 |
| Porsche 977G72 Gemballa | 600 | 840 | 3.5 |

If acceleration of vehicles $a$ is (6):

$$a = \frac{dv}{dt_{ie}} = \frac{d^2s_{ie}}{dt_{ie}^2} ,$$

(6)

jars are (7):

$$j_p = \frac{da}{dt_{ie}} = \frac{d^2v}{dt_{ie}^2} = \frac{d^3s_{ie}}{dt_{ie}^3} .$$

(7)

They can also be expressed as follows (8):

$$j_p = \frac{da}{dt_{ie}} = \frac{da}{dv} \frac{dv}{dt_{ie}} = a \frac{da}{dv} .$$

(8)

The analytical calculation of jars is made somewhat difficult by the fact that graphs of acceleration changes $a = f(t_{ie})$ and $a = f(v_{ie})$ are not usually described analytically. However, the theory of vehicles handles the graphic forms of these functions [1], [13]. Such pictures are obtained during experiments (see Fig. 1) or by using theoretical curves of dynamic factor [1]. If acceleration graph $a = f(v_{ie})$ is
known, by way of its graphical differentiation it is also possible to find jar graph coordinates $da/dt_{ie} - v$ as function $j_p = da/dt_{ie} = f(v)$.

Fig. 1. Sample of oscillogram with a graph of $j_p$.

### III. Behaviour of Jars

Using a sample oscillogram with curve $a = f(t_{ie})$ [1] and graphical differentiation, we can draw a graph of jars in coordinates $j_p - t$ (see Fig.1 in which $a = j$).

We can see from the graph that the maxima of curves $a$ and $j_p$ differ by time.

Maximum values $a$ are reached at the initial phase of vehicle acceleration. For light vehicles (motorcycles, light motorcars), it is reached in the 1st gear during the development of maximum dynamic factor $D_{max}$. For heavy vehicles with multi-stage gear boxes, $a_{max}$ can be reached only in the 2nd or 3rd gear.

The maximum values of jars for all vehicles are reached at the very beginning of run (first seconds). During the acceleration of vehicles, $a$ can reach negative values only during gear shift, but $j_p$ could be obtained each time after reaching $a_{max}$ in each gear.

The graph of jars for each gear used during acceleration can be divided into 4 phases characterising the mode, and in the graph their times are marked as $t_{11}$, $t_{12}$, $t_{13}$ and $t_{pp}$. For example, run up time in the 1st gear (including time used for switching gears to the 2nd gear) consists of a sum made by the times of the 4 mentioned phases (9):

$$t_{w1} = t_{11} + t_{12} + t_{13} + t_{pp} .$$

These phases can be characterised by the following indications:

1. **Beginning of run (in each gear).** During this time period $t_{11}$ there is a fast increase of jars reaching the maximum value in the appropriate gear.
2. **Decrease of jars from the maximum value to a stabilized value** during time period $t_{12}$.
3. **Speeding up with a stabilized value of jars.** During this time period $t_{13}$ the value of jars changes just a little (usually within the limit of error) and it is under zero.
4. **Shifting of gears.** During this time period $t_{pp}$ the value of jars is changing in a wide range, at the beginning up to the maximum negative value and then to zero.
IV. ANALYSIS AND RESULTS

The desired curve of jar behaviour is influenced by two main factors displayed in Fig. 2.

![Diagram of jar behaviour](image)

Fig. 2. Main factors for jar behaviour.

To manufacture vehicles with very good acceleration ability and short run up time for reaching high speed, it is necessary to influence the following two factors:

- inclination angle $\beta$ of the curve at the phase of jar increase $j_p$;
- height of jar average value $\alpha$.

The angle of curve at the beginning of vehicle run up, namely in its 1st phase, should be as wide as possible because the speed of vehicle acceleration increase is characterized by the tangent of this angle, namely in the elementary range (10):

$$\tan \beta = \frac{dj_p}{dt_{ie}}.$$  \hspace{1cm} (10)

Higher speed can be achieved in shorter time when angle $\beta$ is wider.

Higher values of angle $\beta$ can be achieved by the first developing high usable traction force to movers $P_k$ and decreasing resistance powers $\sum P_i$. Theoretically, higher traction force can be developed by enlarging engine torque in the whole speed range by choosing rational total transmission ratios and reducing vehicle mass if we take no notice to factors with apparently lower influence such as the size of movers, radius of wheels, and transmission efficiency.

However, it should be emphasized that this is a matter of practically usable traction force (not a theoretical possibility). It can be quite different from theoretical, because it mainly depends on the adhesion between movers and ground surface characterized by adhesion factor $\phi$. The largest values $a$ and positive $j_p$ can be reached only in case when a very good adhesion between the ground (road) and movers (for example, wheels) is provided at least temporarily, when the value of adhesion factor $\phi$ is approximately 1 or higher, namely $\phi > 1$. Modern vehicles and roads can ensure the fulfilment of this provision.

Adhesion and consequently practical possibilities for using theoretically possible traction force can be enlarged by the appropriate design of movers (for instance, tread pattern), the material of movers maximally appropriated for establishing adhesion and other methods ensuring good adhesion, for example, an automatic device for preventing mover skidding.

Practically, during tests, inclination angle $\beta$ of curve $j_p$ can be considerably influenced by driver’s actions depending on his/her skills and experience and psychophysiological features and character.

The average value of jars can be calculated on the basis of vehicle run up time required for reaching a certain speed. We will calculate it for 3 characteristic cases when vehicles achieve speed $v = 100$ km/h = 27.78 m/s during:

1. 20 s (vehicles with quite poor acceleration capability);
2. 10 s (modern vehicles with quite good acceleration capability);
3. 5 s (some modern vehicles with very good acceleration capability).
Modern vehicles with very good acceleration ability are powerful motorcycles and some motorcars (mostly sport models), for example, *Lansarea CL600* with V12 turbo 5.5 l engine – 4.6 s, *Audi SLS AMG E-CELL* – 4 s, *Porsche 977GT2 Gemballa* – 3.5 s as apparent from Table I.

The results of calculations are given in Table II.

**TABLE II**

| Parameters                  | Values of parameters for reaching a speed of 100 km/h in time |
|-----------------------------|---------------------------------------------------------------|
|                             | 20 s  | 10 s  | 5 s   |
| Average acceleration $a$, m/s$^2$ | 1.39  | 2.78  | 5.56  |
| Average jars $j_p$, m/s$^3$  | 0.07  | 0.28  | 1.11  |

If the maximum values of acceleration are usually 1.5 to 2 times above the average, the maximum values of jars can be considerably (up to 200 times) higher than the average values. The difference between average and maximum $j_p$ values is individual for each particular vehicle. Such a difference as well as good acceleration ability are mostly determined by:

- 1$^{st}$ phase: ensured adhesion, engine power and torque, fast operation of clutch during switching;
- 2$^{nd}$ phase: ensured adhesion, engine power and torque, total transmission ratio;
- 3$^{rd}$ phase: engine power and torque, total transmission ratio;
- 4$^{th}$ phase: in case of automatic transmission – automatic operation of gear switching, in case of non-automatic transmission – operation of gear switching mechanism and nature of operator activity during gear switching.

Additionally, jars are affected by the design and their technical condition of vehicles, streamlining form, weight and other less important factors, as well as the condition of ground.

The first and second phases are the most important for providing excellent acceleration capability.

**V. Conclusion**

In order to characterize the acceleration abilities of vehicles, in addition to common parameters, namely change of speed and acceleration in time, it is required to apply one more parameter: change of acceleration increase in time.

Change of acceleration increase in time $j_p = f(t)$ progresses in 4 specific phases:

1. 1$^{st}$ phase – beginning of acceleration run where $j_p$ is growing rapidly to the maximum value in the respective gear;
2. 2$^{nd}$ phase – $j_p$ decrease from the maximum value to the stabilized value;
3. 3$^{rd}$ phase – speeding up with stabilized value $j_p$
4. 4$^{th}$ phase – shifting when value $j_p$ is changing in a wide range from the maximum negative value to zero.

Factors for providing maximum value $j_p$ and good acceleration ability:

- sufficient power and torque of engine and also good adhesion between the ground and movers (driving elements), $\varphi > 1$ (1$^{st}$, 2$^{nd}$, 3$^{rd}$ phase),
- fast operation of clutches during switching (1$^{st}$ phase),
- operation of gear switching mechanism during switching (1$^{st}$, 4$^{th}$ phase);
- appropriate total transmission ratio (2$^{nd}$, 3$^{rd}$ phase);
- automatic operation of gear switching in case of automatic transmission and nature of operator activity during gear switching in case of non-automatic transmission (4$^{th}$ phase).

The first and second phases are the most important for providing excellent acceleration ability.
The maximum of good acceleration ability can be reached in conditions when the greatest ascent (β) of real curve \( a = f(v) \) is obtained as a result of optimal combination of gain of torque, adhesion factor and total transmission ratio. Therefore, \( j_p \) can be increased by increasing the value of adhesion factor \( \varphi \), ascend of engine torque \( M_e \) and value of \( M_e \) up to the maximum usable value from the point of view of adhesion, as well as by choosing the most appropriate transmission ratios, particularly in the first gears.

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