Influence of the vertical load exerted by the trailer on the coupling device on towing vehicle’s steerability and stability

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Abstract. The paper concerns an analysis of the steerability and stability of a motor vehicle towing a trailer during the double lane change manoeuvre. As results of experimental road tests carried out on an airfield runway, time histories of the following parameters were determined: steering angle, lateral acceleration, and drift angle of the towing vehicle, as well as angular velocity of towing vehicle yaw. The tests were performed for various states of the vertical load exerted on towing vehicle’s coupling device.

1. Introduction

For a trailer to be safely towed, the coupling device components installed on the towing vehicle and on the trailer should be correctly selected and matched up to each other so that adequate cooperation between the vehicles combined together might be ensured. When a tractor-trailer unit is moving, the following forces act on the vehicle coupling device:

1) Tractive force necessary to overcome trailer’s rolling resistance, air resistance, and grade resistance and to accelerate the trailer;
2) Braking force:
   a) for unbraked trailers, the total braking force is transmitted by the coupling device;
   b) for trailers with brakes, a braking force may occur in the coupling device due to imperfect synchronization between the operation of brakes of both vehicles;
3) Vertical forces applied by the drawbar in the case of a centre-axle trailer, pressing down the coupling device.

The coupling devices should meet the following requirements [3, 4]:

– The coupling device components installed on the towing vehicle and on the trailer should be compatible with each other in terms of their dimensional and strength characteristics.
– They shall prevent separation of the vehicles from each other when in motion.
– They shall attenuate any shocks and jerks.
– They shall ensure articulation of the vehicle coupling and enable angular displacement of the longitudinal vehicle centrelines, especially on road bends and uneven ground.
– Their safe coupling and uncoupling shall be possible by one person without the use of tools.
– All the couplings must be made as mechanical connections.
– The longitudinal centreline of the coupling device components should coincide with the longitudinal vertical symmetry plane of the towing vehicle during rectilinear forward motion of the tractor-trailer unit.
- All the couplings shall have positive mechanical engagement and the closed position shall be locked at least once by further positive mechanical engagement.
- The effects of vibration must not cause component parts of the coupling device to move to positions where the device may open or disengage.
- The coupling device on the motor vehicle shall be designed to support the vertical load that might be exerted on it by a centre-axle trailer.

The above shows that the coupling devices must meet various requirements arising from complex issues related to strength of materials, dynamics, and kinematics.

At present, the coupling devices are subject to type-approval requirements laid down in UN ECE Regulation No. 55.01 [4]. It should be stressed here that the type-approval tests do not include road tests, i.e. they are limited to rig tests only. The advisability of the conducting of analyses concerning the dynamics of the mechanical connection between the trailer and the towing vehicle has been shown in publications [6, 7, 8]. In this connection, it has been considered reasonable to undertake the road testing of the coupling devices, with carrying out dynamic measurements in real (road) conditions. It should be stressed here that the complex construction and operation of the coupling devices on the one hand, and their critical importance related to the ensuring of reliable mechanical connection between two (or more) vehicles on the other hand, must be kept in mind. Moreover, the impact of the trailer on the steerability and stability of the towing vehicle must also be taken into consideration.

2. Experimental road tests

Road tests are very important from the explorative and research work point of view. They should not be skipped when the issues related to the tractor-trailer interactions are explored. The mechanical coupling devices and their parts are defined as all the elements of vehicle frame as well as all the load-carrying parts of the motor vehicle and trailer substructure (undercarriage) and superstructure (body) with the use of which the vehicles are coupled together to form a tractor-trailer unit or an articulated vehicle. They also include the permanently fixed or detachable components intended for the fastening or operation of the coupling devices and parts mentioned above [4, 5].

2.1. Vehicle testing during the double lane change manoeuvre [1]

The tests of a tractor-trailer unit during the double lane change manoeuvre according to [1] are carried out in a closed-loop system, i.e. with the driver-vehicle-driver feedback, and they are dedicated to passenger cars and light trucks with up to 3 500 kg GWM (Gross Vehicle Mass). During the test, the vehicle is driven along a prescribed test road section (within a predefined corridor), schematically presented in Figure 1, with a constant speed of \( V = 80 \text{ km/h} \) and with a maximum possible speed. If the vehicle cannot achieve the speed of \( V = 80 \text{ km/h} \), only the latter test option is performed.

![Figure 1. Schematic outline of the test road section (test corridor) during the double lane change manoeuvre: dimensions in [m]; B – vehicle width [1].](image-url)
Based on the test, time histories of the following parameters can be experimentally determined [1]:
- lateral acceleration $a_y(t)$;
- angular velocity $\psi(t)$ of towing vehicle yaw (rotation around the vertical axis);
- roll angle $\phi(t)$ of the towing vehicle (rotation around the longitudinal axis);
- steering torque $M_h(t)$;
- drift angle $\beta = \arctg \frac{V_y}{V_x}$,

where $V_x$ and $V_y$ are longitudinal and lateral components of the vehicle velocity, respectively.

In the tractor-trailer unit, the distribution of the load carried on the trailer was varied with the use of two tanks filled with water, which represented the real trailer loading conditions; the towing vehicle load remained unchanged (the vehicle was loaded to its Gross Vehicle Mass). The trailer load was arranged in two ways, referred to as option I and option II, in order to obtain two different values of the load on the device that coupled the trailer with the motor truck used as the towing vehicle. The values of the coupling device load were selected on the grounds of the data given in the normative documents [2, 5].

The technically permissible maximum load on the coupling point (defined as the mass corresponding to the maximum permissible static vertical load to be transferred by the trailer to the towing vehicle at the coupling point) must be at least equal to 4 % of the Gross Trailer Mass or 25 kg, whichever is the greater (for the trailer under test, the calculated value of the load on the coupling point was 100 kg); the force $P$ necessary to pull the ball out of its socket should meet the inequality below:

$$P > 20 W_s$$

where: $W_s$ – maximum acceptable vertical force applied to the ball socket [N]; $W_s = 300$ N for trailers with a mass of $m_R \leq 430$ kg; $W_s = 7 \% (m_R \times g)$ for trailers with a mass $m_R$ from 431 kg to 1700 kg; $W_s = 1200$ N for trailers with a mass $m_R$ from 1701 kg to 3500 kg; $m_R$ – actual trailer mass [kg].

For the vehicles under test, the value of force $P$ was 24 000 N.

**Option I** (denoted by “PS_NOK”). The arrangement of the test load placed on the trailer corresponded to incorrect distribution of real trailer load in result of which the load on the coupling device was directed opposite to the acceleration of gravity $g$ (i.e. the pressure of the rear axle wheels of the motor vehicle on the road was reduced). In static conditions, the value of the vertical load on the coupling device was $PS = -1118$ N (the load was directed opposite to the acceleration of gravity $g$, i.e. vertically upwards). The distance between the ball of the coupling device and the front plane of the tanks filled with water was 3200 mm.

**Option II** (denoted by “PS_OK”). The arrangement of the test load placed on the trailer corresponded to correct distribution of real trailer load in result of which the load on the coupling device was directed like the acceleration of gravity $g$ (i.e. the pressure of the rear axle wheels of the motor vehicle on the road was increased). In static conditions, the value of the vertical load on the coupling device was $PS = 1746$ N (the load was directed like the acceleration of gravity $g$, i.e. vertically downwards). The distance between the ball of the coupling device and the front plane of the tanks filled with water was 2800 mm.

The view of the trailer prepared for testing has been shown in Figure 2.
2.2. Analysis of the test results

The maximum speed that could be achieved for the manoeuvre to be safely completed (i.e. for the vehicle to go through the whole predefined corridor) was 65 km/h. When the vehicle speed exceeded this limit, trailer wheels were lifted off the road surface. The tests were carried out for option I and option II of trailer load distribution. Time histories of the steering wheel angle $\delta_h$, recorded during the double lane change manoeuvre, have been presented in Figure 3. The following symbols have been adopted: “DMC_65” represents the test drive of the motor vehicle without the trailer, “PS_NOK_65” represents the test drive of the motor vehicle with the trailer loaded to option I, and “PS_OK_65” represents the test drive of the motor vehicle with the trailer loaded to option II.

![Figure 3](image3.png)

**Figure 3.** Time histories of the steering wheel angle $\delta_h$.

The extreme absolute values of the steering wheel angle $\delta_h$ in individual sectors (see Figure 3, cf. Figure 1) were recorded for option II, i.e. PS_OK_65. In the tests of the tractor-trailer unit, lower amplitudes of $\delta_h$ were recorded for option I (PS_NOK_65); however, distinct corrections of the steering wheel angle occurred when the tractor-trailer unit went through sectors 3, 5, and 6 of the test corridor. The extreme absolute values of the steering wheel angle $\delta_h$ in individual sectors of the test corridor have been given in Table 1.
Table 1. Extreme absolute values of the steering wheel angle $\delta_H$ in individual sectors of the test corridor.

| Sector of the test corridor | Absolute value of $\delta_H$ [deg] |
|-----------------------------|-----------------------------------|
|                             | DMC_65   | PS_NOK_65 | PS_OK_65 |
| Sector 1                    | 100.7    | 84.6      | 121.7    |
| Sector 2                    | 88.7     | 67.8      | 116.4    |
| Sector 3                    | 96.3     | 95.2      | 121.2    |
| Sector 4                    | 102      | 62.5      | 126.1    |

For further analysis, the values denoted by DMC_65, recorded in the test during which no force was applied to the coupling device, were adopted as a reference and compared with the extreme absolute values of the steering wheel angle $\delta_H$ in individual sectors of the test corridor. In the test denoted by PS_NOK_65, the extreme absolute values of the steering wheel angle $\delta_H$ were lower by about 40% than the corresponding reference values. Conversely, the extreme absolute values of $\delta_H$ recorded during the test denoted by PS_OK_65 in individual sectors of the test corridor exceeded the reference values by 20-30%.

Figure 4 shows time histories of the lateral acceleration $a_y$, recorded during the manoeuvre under analysis.

![Figure 4](image.png)

Figure 4. Time histories of the lateral acceleration $a_y$.

The lateral acceleration vs. time curves ($a_y = f(t)$) having been recorded are similar to each other in qualitative and quantitative terms, but a phase shift in the $a_y$ amplitudes occurred when the tractor-trailer unit went through sectors 4 and 5 of the test corridor. The extreme absolute values of the lateral acceleration $a_y$ in individual sectors of the test corridor have been given in Table 2. In the test denoted by PS_NOK_65, the absolute values of the lateral acceleration $a_y$ were lower by about 10-20% in sectors 1, 2 and 4 of the test corridor than the corresponding reference values. Conversely, the absolute values of the lateral acceleration $a_y$, recorded during the test denoted by PS_OK_65, were higher by about 10% in sectors 1 and 4 and lower by up to 10% in sectors 2 and 3 as against the corresponding reference values.

Table 2. Extreme absolute values of the lateral acceleration $a_y$.

| Sector of the test corridor | Absolute value of $a_y$ [m/s$^2$] |
|-----------------------------|-----------------------------------|
|                             | DMC_65   | PS_NOK_65 | PS_OK_65 |
| Sector 1                    | 4.6      | 4.1       | 5.0      |
| Sector 2                    | 4.7      | 4.0       | 4.7      |
| Sector 3                    | 4.6      | 4.7       | 4.2      |
| Sector 4                    | 5.2      | 4.1       | 5.4      |
Time histories of the drift angle $\beta$ have been presented in Figure 5. The extreme absolute values of the drift angle $\beta$ in individual sectors of the test corridor have been given in Table 3. The extreme absolute values of the drift angle $\beta$ recorded in individual sectors of the test corridor were highest for the PS_OK_65 option and lowest for the DMC_65 option. It should be simultaneously stressed that growths in the $\beta$ values occurred in the PS_NOK_65 test in sectors 3, 5, and 6 of the test corridor. In the PS_NOK_65 test and the PS_OK_65 test, the absolute values of the drift angle $\beta$ were higher by 5-160 % and by 40-180 %, respectively, than the corresponding reference values.

![Figure 5. Time histories of the drift angle $\beta$.](image)

| Sector of the test corridor | Absolute value of $\beta$ [rad] |
|-----------------------------|---------------------------------|
|                             | DMC_65 | PS_NOK_65 | PS_OK_65 |
| Sector 1                    | 0.028   | 0.029     | 0.054    |
| Sector 2                    | 0.018   | 0.046     | 0.051    |
| Sector 3                    | 0.026   | 0.051     | 0.045    |
| Sector 4                    | 0.035   | 0.041     | 0.050    |

Figure 6 shows time histories of the angular velocity $\psi$ of motor vehicle yaw.

![Figure 6. Time histories of the angular velocity $\psi$ of motor vehicle yaw.](image)

The extreme absolute values of the angular velocity $\psi$ of motor vehicle yaw as recorded in individual sectors of the test corridor were highest for the PS_OK_65 option and lowest for the DMC_65 option. It should be simultaneously stressed that growths in the $\psi$ values occurred in the PS_NOK_65 test in sectors 3, 5, and 6 of the test corridor. The extreme absolute values of the angular velocity $\psi$ of motor
vehicle yaw in individual sectors of the test corridor have been given in Table 4. During the test denoted by PS_NOK_65, the absolute values of the angular velocity \( \psi \) of motor vehicle yaw were lower by 10-15 % in sectors 1 and 4 of the test corridor and higher by about 20-30 % in sectors 2 and 3 than the corresponding reference values. In the test denoted by PS_OK_65, in turn, the absolute values of the angular velocity \( \psi \) of motor vehicle yaw were higher by 20-70 % as against the corresponding reference values during the whole manoeuvre.

**Table 4.** Extreme absolute values of the angular velocity \( \psi \) of motor vehicle yaw

| Sector of the test corridor | \( \psi \) [deg/s] |
|-----------------------------|------------------|
| DMC_65                      | PS_NOK_65        | PS_OK_65        |
| Sector 1                    | 18.89            | 16.82           | 22.80           |
| Sector 2                    | 14.25            | 17.53           | 23.91           |
| Sector 3                    | 16.78            | 21.42           | 19.79           |
| Sector 4                    | 17.94            | 15.22           | 24.20           |

Figure 7 shows time histories of the motor vehicle roll angle \( \phi \).

**Figure 7.** Time histories of the motor vehicle roll angle \( \phi \).

The motor vehicle roll angle vs. time curves \( (\phi = f(t)) \) having been recorded are similar to each other in qualitative and quantitative terms, but a phase shift in the \( \phi \) amplitudes occurred when the tractor-trailer unit went through sectors 2, 3, 4 and 5 of the test corridor. Moreover, growths in the \( \phi \) values occurred in the PS_NOK_65 test in sectors 3, 5, and 6 of the test corridor. The extreme absolute values of the motor vehicle roll angle \( \phi \) have been given in Table 5. In the test denoted by PS_NOK_65, the absolute values of the motor vehicle roll angle \( \phi \) were lower by up to 10 % in sectors 2, 3, and 4 of the test corridor than the corresponding reference values. During the test denoted by PS_OK_65, the absolute values of the motor vehicle roll angle \( \phi \) were lower by 3-20 % than the corresponding reference values in the same sectors (2, 3, and 4) of the test corridor. Based on the recorded time histories of the values of the steering wheel angle \( \delta_H \), lateral acceleration \( a_y \), drift angle \( \beta \), angular velocity of motor vehicle yaw \( \psi \), and motor vehicle roll angle \( \phi \), a statement may be made that differences existed between dynamic characteristics of the vehicles subjected to the DMC_65, PS_NOK_65, and PS_OK_65 test options. The qualitative and quantitative differences show that:

– the impact on lateral dynamic behaviour of vehicle articulated with trailer;
– the value of the static load on the coupling device affects the steerability and stability of the towing vehicle.
### Table 5. Extreme absolute values of the motor vehicle roll angle $\varphi$

| Sector of the test corridor | Absolute value of $\varphi$ [deg] |
|-----------------------------|----------------------------------|
|                             | DMC_65  | PS_NOK_65 | PS_OK_65 |
| Sector 1                    | 3.46    | 3.49      | 3.67     |
| Sector 2                    | 3.59    | 3.35      | 3.48     |
| Sector 3                    | 4.18    | 4.17      | 3.43     |
| Sector 4                    | 3.94    | 3.42      | 3.61     |

### 3. Conclusions

When a tractor-trailer unit is moving, the towing vehicle is subjected to the impact of significant forces applied by the trailer to the mechanical coupling device. They chiefly consist of time-varying longitudinal forces occurring when the vehicle is braked or accelerated, lateral forces generated when the vehicle is turning or moving on a road bend, and vertical forces. The values of all of them depend on the vertical load exerted by the trailer drawbar. Due to the fact that the type-approval tests of coupling devices do not include road tests (they are limited to rig tests only), the knowledge of trailer’s influence exerted through the coupling device on towing vehicle’s steerability and stability is rather inadequate. Therefore, it is recommendable to carry out dynamic road tests to explore this issue. The results obtained from this analysis show the reasonability of conducting research on the influence of the vertical load exerted by the trailer on the coupling device on towing vehicle’s steerability and stability.

Based on the presented test results, a statement may be made that the maximum values of the parameters examined were not always associated with the case that incorrect load was applied to the coupling device. In such cases, however, the driver had to correct additionally the vehicle trajectory with the steering wheel for the tractor-trailer unit to be kept within the predefined corridor. The necessity to make the additional corrections indicates, therefore, a reduction in the intrinsic system capability to attenuate the oscillations of the transient process and deterioration in the stability of the tractor-trailer unit.

By extending the scope of the road testing to other tests, such as circular driving test or test with a jerk applied to the steering wheel, other information may be obtained, e.g. regarding the oversteering or understeering of the towing vehicle.

### References

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