Influence of harsh braking parameters on safety of load transport

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Abstract. Loads acting on transported cargo are the result of the inertia forces associated with the movement of the motor vehicle. Longitudinal inertia forces acting on the goods transported by a vehicle may result from accelerating or braking the car. The maximum values of acceleration acting on cargo are important in terms of the selection of methods and tools used to secure the transported goods.

The paper presents the results of experimental tests of harsh braking of a tractor unit with a semi-trailer. The experiment was divided into three measurement series. Two of them were carried out on asphalt pavement, while the last one was carried out on concrete pavement. One series consisted of ten braking tests. The values of maximum decelerations recorded during the tests were subjected to statistical analysis and then compared with the values of the average full deceleration of braking determined for individual braking cases.

Keywords: road transport safety, cargo transport safety, cargo securing, harsh braking

1. Introduction

Due to the wide availability of infrastructure and high versatility, road transport is currently the most popular means of transport and considered the most important branch of European transport. It enables the execution of transport tasks virtually from any place and at any time, day or night. The widespread use of road transport is also the result of the high availability of cargo space, enabling the transport of virtually any cargo.

The benefits resulting from the development of road transport are also accompanied by hazards to the environment and road transport safety. This is manifested, inter alia, by the increased emission of pollutants and the increased number of various types of road accidents. It is estimated that almost a quarter of the accidents involving heavy goods vehicles are the result of improper cargo securing [1, 2]. The growing demand for transport services leads to increased safety risks for people involved in the transport process and other road users, as well as for vehicles and the loads they transport.

The main element affecting the safety of cargo transport is proper securing by selecting the appropriate methods and devices to secure the goods transported in the vehicle's cargo space. The cargo may be secured by blocking, lashings, increasing the friction force against the floor of the body or surface securing [3, 4, 5]. The selection of the appropriate method and the selection of tools for securing loads during transport depends on the forces acting on the cargo while the vehicle is moving. The loads acting on the cargo during transport result from inertia forces related to the movement of the motor vehicle, vibrations and inclination of the vehicle. The inertia forces acting on the load while the
vehicle is moving are longitudinal force occurring during acceleration and braking, lateral forces occurring due to bendiness, vertical forces generated when driving on uneven roads [6, 7, 8].

The longitudinal inertia force is generated when the speed of the vehicle is changing, i.e. when the vehicle is braking or accelerating. The force can be expressed as the product of the mass of the cargo and acceleration of the mass centre. The maximum values of acceleration acting on the load are important in terms of selecting methods and tools used to secure the transported loads.

A significant percentage of road incidents caused by improper securing of loads was the reason to analyse the accelerations recorded during a series of harsh braking and acceleration tests of an articulated vehicle. The paper describes the object of the test, the test conditions, as well as the results of tests, showing the properties of the longitudinal dynamics of an unloaded truck.

2. Methodology of field tests

2.1. Research vehicle

In the years 2019-2021, the Department of Motor Vehicles and Transport of the Kielce University of Technology conducted research in the field of longitudinal dynamics (acceleration and braking) and transverse dynamics of vehicles of the following category: M1, M2, M3, as well as N1 and N3.

The present study presents and analyses the results of road tests of an articulated vehicle, consisting of a tractor unit and a semi-trailer (Fig. 1), classified as category N3. The N3 category includes the vehicles adapted to transport cargo of the maximum mass exceeding 12 tonnes. The total length of the vehicle was 12.3 m. The tractor unit had two single axles with a wheelbase of 4 meters, while the semi-trailer had three axles. The test weight, i.e. the tare weight of the tractor unit and semi-trailer, as well as the test apparatus and two people, was 13,450 kg in total. The tractor unit was equipped with 315/70/22.5 tyres, while the semi-trailer with 385/65/22.5 tyres.

2.2. Measuring apparatus

All the results obtained and presented in this study were recorded using the constructed measurement track that consisted of:

- the S-350™ optoelectronic head of the Correvit system for non-contact measurement of velocity vector components (speed measurement range 0.5 ÷ 250 km/h, measurement range of the lateral drift angle ± 40°, measurement resolution of the lateral drift angle <± 0.1°) [9],
- TANS™ gyro sensor for measuring linear accelerations (measuring range ± 3 g) and angular velocities (yaw speed range ± 150 deg/s) [10],
- data acquisition stations µEEP-12 [11],
- laptop and software.

The arrangement of the constructed measurement track allowed to record:

- longitudinal and lateral speed, as well as the vehicle’s chassis drift angle,
- longitudinal, lateral and vertical accelerations and angular velocities of the body (driver’s cab).
2.3. The course of the test

The longitudinal dynamics tests were carried out on two types of pavement (dry asphalt and dry concrete). The asphalt pavement was in good technical condition, while the concrete pavement was covered with some small pieces of concrete debris. In this study, three series of measurements were analysed during which the following was performed:

- harsh braking of the vehicle on dry concrete pavement at a speed of 30 km/h,
- harsh braking of a vehicle on a dry asphalt pavement at a speed of 30 km/h and 50 km/h.

Each measurement series consisted of ten braking tests, during which the following time curves were recorded: the longitudinal and lateral velocity, as well as the vehicle’s chassis sideslip angle; longitudinal, lateral and vertical accelerations and angular velocities of the driver’s cab. The time curves of the above-mentioned values recorded during braking on a dry asphalt pavement at the initial speed of 50 km/h, are shown in Figure 2. For each of the braking tests, the value of the maximum braking deceleration \( a_{\text{max}} \) and the mean full developed deceleration value (MFDD) were determined.

![Figure 2. Sample time curves of selected values recorded during the braking test](image)

3. Results and analysis of the tests

In the course of the research, the longitudinal acceleration of the vehicle was recorded using the acceleration sensor installed in the driver’s cab. The time curves of these accelerations are shown in Figure 3. For each of the braking tests, the value of the maximum braking deceleration \( a_{\text{max}} \) was determined. Based on these values, for each series consisting of ten braking tests, the following values were calculated: the highest (\( a_{\text{max}} \)) and the lowest (\( a_{\text{min}} \)) maximum deceleration, a mean value of maximum decelerations \( \bar{a}_{\text{max}} \) and its standard deviation \( \text{SD}\bar{a}_{\text{max}} \). The calculation results are presented in Table 1.

| Type of road pavement | Initial speed, km/h | Statistics of maximum decelerations, m/s\(^2\) |
|-----------------------|---------------------|-----------------------------------------------|
|                       | \( a_{\text{max}} \) | \( a_{\text{min}} \) | \( \bar{a}_{\text{max}} \) | \( \text{SD}\bar{a}_{\text{max}} \) | Q0.1 | Q0.9 |
| Dry asphalt pavement   | 30                  | 10.64 | 6.55 | 8.66 | 1.24 | 10.15 | 7.16 |
|                       | 50                  | 9.61  | 8.11 | 8.83 | 0.45 | 9.28  | 8.28 |
| Dry concrete pavement  | 30                  | 9.59  | 7.57 | 8.31 | 0.65 | 9.22  | 7.72 |
Figure 3. Longitudinal accelerations curves recorded during braking tests, carried out on the following pavement: a) dry asphalt at a speed of 30 km/h, b) dry asphalt at a speed of 50 km/h, c) dry concrete at a speed of 30 km/h.

A preliminary analysis of the above diagrams and the values summarised in Table 1 show that, in the individual measurement series, there is a high qualitative and quantitative similarity between the deceleration curves. All the graphs clearly show the effect of the ABS system activation and the tractor cabin rocking effect. The rocking of the body (cab) is most evident in the final stage of the braking (just before and immediately after stopping the vehicle).

The highest mean value of the maximum decelerations $a_{max}$ amounting to 8.83 m/s$^2$ was recorded during the series of tests carried out on an asphalt pavement at the initial vehicle speed of about 50 km/h. It was only 6.6% higher than $a_{max}$ recorded for the series of tests carried out on dry concrete pavement at the initial vehicle speed of about 30 km/h.

For the tests carried out at the initial speed of 30 km/h, the average value of the maximum decelerations for the tests carried out on the concrete pavement was lower than the average value of the maximum decelerations for the tests carried out on the asphalt pavement.

The international requirements for braking systems are regulated by the provisions of the United Nations Economic Commission for Europe. They are included in several regulations on the approval of braking systems. One of them is UN/ECE Regulation No 13 "Uniform provisions concerning the approval of vehicles of categories M, N and O with regard to braking". As regards the approval of braking systems, the national regulations are harmonised with the international ones.

According to the regulation, the effectiveness of the braking systems is determined by measuring the stopping distance of the vehicle from a given initial speed or from the mean fully developed deceleration.

The stopping distance is the distance travelled by the vehicle from the moment the driver begins to depress the brake pedal until the vehicle comes to a stop, and can be determined using the formula:

$$S_z = S_R + S_H = V_0 \cdot \left( t_r + \frac{t_n}{2} \right) + \frac{V_0^2}{2 \cdot MFDD} \ [m]$$ (1)
while the braking distance can be determined based on the following dependence:

$$S_H = \frac{V_0^2}{2 \cdot MFDD} \ [m]$$ (2)

Initial speed ($V_0$) means vehicle speed at the moment the driver begins to depress the brake pedal. Whereas the mean fully developed deceleration ($MFDD$) is the average deceleration on the road in the speed range of $V_b$ to $V_e$ and they were calculated based on dependence number 3 [12]:

$$MFDD = \frac{V_b^2 - V_e^2}{25.92 \cdot (S_e - S_b)} \ [m/s^2]$$ (3)

where:
- $V_0$ - initial vehicle speed in [km/h],
- $V_b$ - vehicle speed corresponding to 0.8 $V_0$ in [km/h],
- $V_e$ - vehicle speed corresponding to 0.1 $V_0$ in [km/h],
- $S_b$ - distance travelled between $V_0$ and $V_b$ in [m],
- $S_e$ - distance travelled between $V_0$ and $V_e$ in [m].

Using the dependence 2 and the recorded time curves of velocity (examples of which are presented in Fig. 4) for each of the tests, the following were determined: $V_0$, $V_b$, $V_e$, $S_b$, $V_e$, MFDD, and $S_H$ and the results of the calculations are given in Table 2.

![Figure 4](image-url)

**Figure 4.** Examples of time curves of longitudinal deceleration and longitudinal speed recorded during braking on the following pavements: a) asphalt, at a speed of 30 km/h, b) asphalt, at a speed of 50 km/h, c) concrete, at a speed of 30 km/h.
### Table 2. Parameters of the truck braking process course

| Test no. | Initial vehicle speed, $V_o$, km/h | Maximum deceleration, $a_{\text{max}}$, m/s$^2$ | Mean fully developed deceleration, $\text{MFDD}$, m/s$^2$ | Braking distance, $S_H$, m |
|----------|----------------------------------|---------------------------------------------|-------------------------------------------------|----------------------------|
|          | Assumed                          | Actual                                      |                                                 |                            |
| Asphalt pavement |                                  |                                             |                                                 |                            |
| 1        | 31.91                           | 6.55                                        | 5.08                                            | 7.74                       |
| 2        | 31.27                           | 8.83                                        | 5.17                                            | 7.30                       |
| 3        | 30.88                           | 10.61                                       | 4.73                                            | 5.16                       |
| 4        | 31.49                           | 7.16                                        | 5.29                                            | 6.94                       |
| 5        | 31.89                           | 8.72                                        | 5.29                                            | 7.42                       |
| 1        | 52.33                           | 8.29                                        | 6.49                                            | 16.29                      |
| 2        | 52.61                           | 9.00                                        | 6.88                                            | 15.35                      |
| 3        | 51.22                           | 8.63                                        | 6.76                                            | 6.78                       |
| 4        | 51.66                           | 9.60                                        | 6.79                                            | 15.18                      |
| 5        | 50.62                           | 8.66                                        | 6.96                                            | 14.20                      |
| Concrete pavement |                                  |                                             |                                                 |                            |
| 1        | 32.86                           | 7.57                                        | 6.20                                            | 6.72                       |
| 2        | 32.90                           | 7.98                                        | 5.24                                            | 7.96                       |
| 3        | 31.43                           | 9.59                                        | 6.00                                            | 5.914                      |
| 4        | 32.33                           | 8.43                                        | 6.16                                            | 6.55                       |
| 5        | 31.81                           | 8.80                                        | 5.97                                            | 6.53                       |

A detailed analysis of the time curves of accelerations and longitudinal velocities, as well as the values listed in Table 2 enables us to conclude that:

- The greatest value $\text{MFDD}$ amounting to 6.96 m/s$^2$ was recorded for the sudden braking test carried out on the asphalt pavement from the initial speed of the vehicle, amounting to 50.62 km/h. This value was over 47% higher than $\text{MFDD}$ determined during the test carried out on the same pavement but with an initial speed of 30.88 km/h.
- The initial speed of the vehicle had a significant impact on the values of $\text{MFDD}$. For tests carried out on dry asphalt pavement, the initial speed increase from the range 30.88 - 31.98 km/h to the range of 50.62 - 52.61 km/h caused the increase of $\text{MFDD}$ from 5.16 m/s$^2$ to 6.78 m/s$^2$.

When selecting the cargo securing elements, take into account the values of forces that may act on the cargo while driving. According to the standard, the maximum values of forces that should be taken into account in the selection of fastening elements are part of the cargo gravity force ($Q_L$) expressed by coefficient $C_{x, y, z}$ [13, 14].

$$C_x = \frac{a_x}{g}$$  \hspace{1cm} (4)

Taking into account the dependence (4), the maximum deceleration values and the determined mean fully developed decelerations $\text{MFDD}$, $C_x$ was determined for each of the tests. The results of the $C_x$ calculations are given in Table 3.
Table 3. Values of the $C_x$ coefficient for selected (example) braking tests.

| Test no. | Initial vehicle speed, $V_0$, km/h | Maximum deceleration, $a_{\text{max}}$, m/s$^2$ | $C_x$ factor for maximum deceleration | Mean fully developed deceleration, MFDD, m/s$^2$ | $C_x$ factor for fully developed deceleration |
|----------|-----------------------------------|-----------------------------------------------|---------------------------------------|-----------------------------------------------|-----------------------------------------------|
|          | Assumed                           | Actual                                        |                                       |                                               |                                               |
| 1        | 30                                | 31.91                                         | 6.55                                  | 0.67                                          | 5.08                                          | 0.52                                          |
| 2        | 30                                | 31.27                                         | 8.83                                  | 0.90                                          | 5.17                                          | 0.53                                          |
| 3        | 30                                | 30.88                                         | 10.61                                 | 1.08                                          | 4.73                                          | 0.48                                          |
| 4        | 30                                | 31.49                                         | 7.16                                  | 0.73                                          | 5.52                                          | 0.56                                          |
| 5        | 30                                | 31.89                                         | 8.72                                  | 0.89                                          | 5.29                                          | 0.54                                          |
| 1        | 50                                | 52.33                                         | 8.29                                  | 0.85                                          | 6.49                                          | 0.66                                          |
| 2        | 50                                | 52.61                                         | 9.00                                  | 0.92                                          | 6.88                                          | 0.70                                          |
| 3        | 50                                | 51.22                                         | 8.63                                  | 0.88                                          | 6.76                                          | 0.69                                          |
| 4        | 50                                | 51.66                                         | 9.60                                  | 0.98                                          | 6.79                                          | 0.69                                          |
| 5        | 50                                | 50.62                                         | 8.66                                  | 1.24                                          | 6.96                                          | 0.71                                          |

|          | Assumed                           | Actual                                        |                                       |                                               |                                               |
|          | Asphalt pavement                  |                                               |                                       |                                               |                                               |
| 1        | 30                                | 32.86                                         | 7.57                                  | 0.77                                          | 6.20                                          | 0.63                                          |
| 2        | 30                                | 32.9                                         | 7.98                                  | 0.81                                          | 5.24                                          | 0.53                                          |
| 3        | 30                                | 31.43                                         | 9.59                                  | 0.98                                          | 6.00                                          | 0.61                                          |
| 4        | 30                                | 32.33                                         | 8.43                                  | 0.86                                          | 6.16                                          | 0.63                                          |
| 5        | 30                                | 31.81                                         | 8.8                                   | 0.90                                          | 5.97                                          | 0.61                                          |
|          | Concrete pavement                 |                                               |                                       |                                               |                                               |

4. Conclusions
The analysis of the tractor unit harsh braking road test results leads to the following conclusions:

- The average value of the maximum deceleration was 8.6 m/s$^2$ and it is more than 45% higher than the mean value of fully developed deceleration.
- The values of $MFDD$ for a series of braking tests carried out on the asphalt pavement at the initial speed of 50 km/h are within a fairly narrow range of 6.49 m/s$^2$ to 6.96 m/s$^2$. For the other two series, these ranges are much wider.
- Significant impact on the values of $MFDD$ had the initial speed of the vehicle and the type of road pavement.
- The highest value of $MFDD$ was recorded for the braking performed on the asphalt pavement at the initial speed ranging from 50.62 km/h to 52.61 km/h, while the lowest value of $MFDD$ was recorded during braking on the asphalt pavement at the initial speed ranging from 30.88 km/h to 31.91 km/h.
- The values of Cx determined based on $MFDD$ range from 0.48 to 0.71 and are definitely lower than the standard value of the Cx index, which is 0.8. This dependence is favourable because the actual values of the forces acting on the cargo during harsh braking will be much lower than the forces determined based on the standard Cx value. The fastening equipment selected on this basis will fully protect the cargo against moving on the floor of the trailer.

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