Evaluation of the safety of overweight and/or oversized traffic based on the analysis of lateral acceleration during transport

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Abstract: Ensuring the safety and smoothness of road traffic in transports, which by their parameters may cause a special situation in road traffic, is the primary task of the team of workers accompanying overweight and/or oversized vehicles. In order to successfully carry out such an activity, it is necessary not only the appropriate technical equipment but also the knowledge of accompanying staff on the issue of critical points during transport and knowledge of how to prevent the danger in the most appropriate way. For these reasons, there is a need to focus the interest of companies on the course of such transport and to increase the safety of all road users through trained staff to accompany vehicles performing overweight and/or oversized transport.

Keywords: safety, vehicle movement, road safety

1. Introduction
We encounter overweight and/or oversized traffic almost every day on the road. Usually, we do not even realize that he is an exceptional participant in road traffic. Only when the vehicle exceeds certain parameters (mostly dimensional) does it become interesting for other road users. Such an approach is not entirely correct because it is not always what is large and dangerous. There are situations where excessively heavy loads can cause great danger during transport and may not be dimensionally abnormal to capture our attention.

Therefore, to avoid road users having to estimate whether a given vehicle is dangerous, there are accompanying vehicles and the whole system of overweight and/or oversized traffic. This system should ensure, first and foremost, the safety but also the flow of road traffic during such services. Traffic safety conditions are also determined by drivers, vehicles, and the driving environment [1]. It is not enough to have an experienced escort team to eliminate the danger. Vehicle drivers also have a share in the level of safety during such transport. From the point of view of safety, it is also necessary to take into account the fastening and movement of the goods on the loading surface of the vehicle. While driving, various forces act on the vehicle and affect the movement of the goods. A study in which Gnap et al. deals with the measurement of these dynamic events using MEMS sensors at selected locations of the vehicle loaded with cargo and changes in dynamics after certain events that could occur during regular road haulage in order to analyse the possibilities of monitoring accelerations and related forces. acting on the load during transport [2].

Ensuring the safety and smoothness of road traffic in transports, which by their parameters may cause a special situation in road traffic, is the primary task of a team of workers accompanying overweight and/or oversized vehicles.
In order to successfully carry out such an activity, it is necessary not only the appropriate technical equipment, but also the knowledge of accompanying staff on the issue of critical points during transport and knowledge of how to prevent the danger in the most appropriate way. For these reasons, there is a need to focus the interest of companies on the course of such transport and to increase the safety of all road users through trained staff to accompany vehicles performing overweight and/or oversized transport.

This paper deals in more detail with the process of transporting overweight and/or oversized loads by measuring transverse and longitudinal accelerations, analysing the measured values, and identifying critical points on the observed routes.

2. State of knowledge

The field of overweight and/or oversized transport, which includes taking into account its safety, the emergence of many events during such transport, the simplification of the authorization process, and other issues in this area are addressed worldwide by many experts not only in the field of road transport. The JRelčák, J. Vrábel and M. Kiktová in the article Using of different road vehicle combinations for abnormal transports based on the assessment of load rating of bridges in Slovakia for the most critical vehicle combination from 2018 [3]. By identifying and assessing such a critical combination, the carrier would be able to carry out an unusual transport with all the vehicles in the fleet on the route under assessment without further evaluation of the route for another vehicle/vehicle combinations. This paper explains and compares several ways to obtain the most critical vehicle/vehicle combination and its purpose.

In their article [4] of 2015, Mr. P. Godavarthy, Mr. Russell, and Mr. Landman deal with the issue of the passage of roundabouts for vehicles with special traffic and, in particular, for oversized vehicles. In the study, they designed six standard roundabouts through which oversized vehicle crossings were subsequently simulated. This study evaluated the effectiveness of the respective vehicles. The disadvantageous proposals resulting from the studies are the impossibility of modifying the middle island by planting plants and greenery.

In 2017, J. Vrábel, J. Jagelčák, O. Stopka, M. Kiktová, and J. Caban dealt with the transport of various types of cargo with different dimensions exceeding the maximum permissible vehicle dimensions. This contribution concerns the main load whose dimensions exceed those of the semi-trailer. The paper describes the maneuverability circle of the vehicle, which states that each vehicle must be able to maneuver in the inner circle of 5.3 m as a minimum criterion and must be able to maneuver in the outer circle of 12.5 m as a maximum criterion. The paper also describes the effect of the position of the fifth wheel on the truck on the total length of the articulated vehicle, which is the maximum allowed length of the load in the rearward direction. This research study indicates the exact length of the maximum load in terms of its width and its location on the loading area of the semi-trailer [5].

The system described in the article [6] by D. Bazaras, N. Batarliene, R. Pašaitis, and A. Petraška is suitable for use in the planning and design of excessive or excessive cargo transport. This system allows objectively the most suitable sections of the route in the existing road network. It is also a means of comparing different layers in a given area, which allows you to objectively select the most suitable one according to certain criteria using mathematical calculations. The paper states that the system is necessary and can be used to compare different modes of transport for oversized and oversized loads for different modes of transport.

The issue of the generation of vibrations, their measurement, and analysis in road transport in India as a result of road inequalities are addressed in the article [7]. Its authors find that the most common road bumps, such as potholes and bumps, disrupt travel and cause great damage to vehicles. Recording road gaps and road roughness levels are key to monitoring road conditions that have an impact on traffic safety and driving comfort. This paper proposes a method that aims to monitor road surfaces, detect potholes and road bumps, and predict their severity by analysing the vertical vibrations of the signals produced by the vehicle as it moves.

Road irregularities, their position recording, and analysis are dealt with in the article [8], which elaborates on the issue of potholes, manhole covers and faulty cracks in the roadway. They say that current ways of monitoring the road surface in many countries depend on driver reports. However, these
methods are usually accompanied by long delays, making it difficult to obtain up-to-date information on road conditions. They tested the system in real conditions on the road. They found the detected conditions on the road on online maps.

Similar to the paper [9], the authors deal with the collection of data on road inequalities through the use of automatic detection of potholes and vehicle speed, which were recorded together with their coordinates and their severity using the built-in Android accelerometer system. A three-axis accelerometer was used along with GPS sensors. They performed such data collection on a 4 km straight road at different speeds and evaluated the data. Subsequently, they divided the potholes into several categories according to the severity of the deviation in the Z axis. The accuracy of the proposed record in comparison with the manual recording of inequalities was 93.75%. The advantage of this method of data acquisition is cost-effectiveness and ease of use.

Authors from China address the analysis and discussion of dimensional, axle loads and weights for road vehicles in their paper [10]. The authors of this article discuss, using comparative analysis of dimensions, axle loads and vehicle weight, which standard would be most suitable for the real needs of road transport. They compare five completely different countries, continents with completely different legislation. They compare China, Japan, Europe, America and Australia. Their comparison shall include the width of the lanes and the maximum permitted width of the combination, the maximum permitted lengths of the combinations according to the composition of the vehicles in the combination and the maximum permitted heights of the combinations. They included the axle load for the given number of axles and the total weight in the comparison of the maximum permissible weights.

The authors deal with a similar issue in their articles [11,12], where they comprehensively discuss the issue of overweight and oversized traffic in the given study, primarily focusing on crossing bridges during such transports. In this study, an analysis of the legislation in individual foreign countries was performed. This was followed by an in-depth analysis of the issues associated with crossing the bridges, also by measuring the emerging phenomena. The results of their study will enable them to make informed decisions issued when issuing permits for the performance of special transport. This should improve and unify current permitting procedures.

The area of overweight and oversized transport, specified in more detail for the transport of wind turbines and their parts, is addressed by the authors in their contribution [13]. The analysis found that the road infrastructure had to accommodate a wide range of complex vehicle configurations to transport wind turbine components, which are often considered overweight and/or oversized by transport authorities in terms of size and weight. The result of the authors' activities and their analysis is an overview of the identified difficulties that occurred during the road transport of wind turbine components. The authors' suggestions, after analysing the issue, include an operational planning strategy based on the maximum width required for the passage of the set transporting the turbine rotor blades. The authors performed a detailed analysis of vehicle dimensions and weights [14,15]. During the processing of the transport, an abnormal transport of up to 60 tons was evaluated in relation to the combined transport.

3. Data and Methods
During the curve, it is possible to equivalently replace the action of the centrifugal force \( F_c \) in the center of gravity of the vehicle \( T \) (Figure 1), which is caused by lateral reactions in the contact surfaces of the tires, i.e. the lateral guiding forces \( F_{bpl}, F_{bpp}, F_{bzl} \) and \( F_{bzp} \). With these forces, the tires counteract the effects of centrifugal force.
Figure 1. The effect of centrifugal force and lateral forces on the car when passing through a curve [16]

If we assume that the forces in Figure 1 in the direction of the x and y axes of the intended coordinate system are in equilibrium with each other, then the equation applies:

$$F_o = F_{bpl} + F_{bpp} + F_{bzl} + F_{bzp}$$

(1)

3.1. Driving in a curve with a transverse slope of the road

Driving in a cross-country curve is divided into:

- driving in a curve that is inclined inwards,
- driving on a bend tilted to the outside.

3.2. Riding in a curve that is inclined inwards

When driving in a curve that is inclined inwards (to the inside), there is a lower risk of overturning or skidding out of a curve compared to driving on a curve without a transverse slope, with the same vehicle input parameters, since point A - Figure 2, which is the tipping point, shifts higher, and therefore the resultant forces R acting on the vehicle can reach a greater angle with respect to the weight of the vehicle, and this means that the centrifugal force $F_o$ can have a higher value.

Figure 2. Rollover vehicle with different road gradients [16]
For this reason, it is sufficient to take into account the slope of the road to the outside (so-called out of the curve) in the calculations. In this case, the centrifugal force $F_o$ is less than when passing the curve on without a lateral inclination, and it is sufficient for the vehicle to roll with less transverse acceleration, i.e., the speed of the combination was lower.

A problem when driving in a curve that is inclined inwards can occur when there is a surface with a reduced coefficient of shear friction in the curve. Then the car can skid not only at a very low speed, which we calculate:

$$v_{2_{\text{min}}} = \sqrt{\frac{tg\beta - \mu_b}{1 + \mu_b * tg\beta} * g * r} \quad (2)$$

Where $\beta$ is the angle of inclination of the road, $\mu_b$ is the coefficient of shear friction, $g$ is the gravitational acceleration in m.s$^{-2}$ and $r$ is the radius of a curve in meters.

3.3. Riding in a curve tilted to the outside

Compared to a curve tilted inwards, in a curve tilted to the outside, the component of gravity $G \cdot \sin\beta$ acts in the same direction as the centrifugal force, so that the vehicle is more prone to overturning (Figure 3). The ability to "resist" lateral skid is also less because the centrifugal force component $F_o \cdot \cos\beta$ "lightens" the vehicle and reduces the frictional force on the contact surfaces of the tires.

![Figure 3. Effect of forces on the car when passing on a curve without a transverse slope [16]](image)

We calculate the maximum speed at the overturning limit $v_{1_{\text{max}}}$ from the following equation (the equation applies to $\tan\beta \leq a / 2h_T$):

$$v_{1_{\text{max}}} = \sqrt{\frac{a - 2h_T * \tan\beta}{2h_T + a * \tan\beta} * g * r} \quad (3)$$

and the maximum speed at the slide limit $v_{2_{\text{max}}}$ is calculated from the following equation (the equation applies to $\tan\beta \leq \mu_b$):

$$v_{2_{\text{max}}} = \sqrt{\frac{\mu_b - \tan\beta}{1 + \mu_b * \tan\beta} * g * r} \quad (4)$$

where $\beta$ is the angle of inclination of the road, $\mu_b$ is the coefficient of slide friction, $g$ is the gravitational acceleration in m.s$^{-2}$ and $r$ is the radius of the curve in meters.
4. Measurements

Overweight and oversized transport - measurement on the section Skalica - Trnava

On 14.2.2021 and 15.2.2021, measurements were performed on one of the parts of overweight and oversized turbine transport on the Plzeň, Doosan Škoda Power (CZ) - Mochove (SK) transport route. The cargo was transported by a company from the Czech Republic and in the territory of the Slovak Republic this transport was accompanied by a company operating in the conditions of the Slovak Republic. The vehicle set had the following parameters:

- Truck-Type: Mercedes Arocs 4 axles,
- semi-trailer-Type: Goldhofer,
- push - Type: Volvo,
- number of axles: 16 pcs tractor + semitrailer, + 4 pcs push,
- maximum width: 3.22 m,
- maximum height (increased): 5.15 m (5.40) m,
- total length: 39.80 m,
- total weight: 110.6 + 41.7 t.

Visual representation of the tractor (front view) and the loaded load on the trailer (rear view is like a technical drawing prepared in the AutoCAD software in Figure 4.

![Figure 4. Technical drawing of the combination with a load - front and rear view [authors]](image)

The longitudinal, transverse and vertical acceleration of the combination was recorded on the route using a recording device, which was then evaluated using an appropriate program. The device was placed just in front of the load on the chassis in the horizontal direction of the axis of the centre of gravity (centre of the width of the loading surface of the chassis). In FIG. 5 is indicated by a red arrow the location of the recording equipment on the technical drawing of the side view of the push-mounted combination.
Figure 5. Technical drawing of the vehicle combination - side view with the location of the recording equipment [authors]

4.1. Measurement procedure
An important part of research is the measurement process. The following table (Table 1) shows the characteristics of the measurement steps performed.

Table 1. Elaboration of measurement procedure during research [authors]

| Measurement step | Measurement procedure |
|------------------|-----------------------|
| 1                | Measurement of the width, height and length of the combination, including the load, by means of a laser distance meter. Location of the recording equipment together with the power supply on the combination chassis at a possible mounting point on the metal part of the chassis as close as possible to the center of gravity of the load. |
| 2                | Check the longitudinal and transverse parallelism of the installed equipment with the combination chassis using a spirit level and a length gauge. |
| 3                | Connecting the device to the power supply immediately before the start of the ride - start of data recording. |
| 4                | Visual inspection of device functionality and data logging via LEDs. |
| 5                | After a maximum of 3 hours 30 minutes, download the recorded data from the device (time determined during the test measurements, the limiting factor is the memory of the device). Possibility to download data even earlier according to the route itinerary. |
| 6                | Data evaluation and creation of graphical output. |
| 7                | Repetition according to the required number of shipments |

4.2. Analysis of curve from route measurement data

Calculation of the centre of gravity height and determination of the lateral shear coefficient for the combination with the load
Calculation of the centre of gravity of the set with the load on the route Skalica - Trnava:

\[
\begin{align*}
h_{TS-T} &= \frac{m_P \cdot v_{TP} + m_N \cdot v_{TN}}{m_P + m_N} = \frac{31 \, 200 \, kg \cdot 0.625 \, m + 11 \, 060 \, kg \cdot 3.438 \, m}{31 \, 200 \, kg + 110 \, 600 \, kg} = 2.819 \, m
\end{align*}
\]

Sample calculation for a left-hand curve in the village of Jablonica (route: Skalica - Trnava)
The measured values at the maximum lateral acceleration during transport in a curve are as follows:
- truck speed: 4.05 m.s\(^{-1}\)
gravitational acceleration multiple for lateral acceleration (k): 0.112

Calculation of turning radius using orthophoto map in a given locality:

\[
r_M = \frac{t^2 + 4 \cdot h^2}{8 \cdot h} = \frac{67^2 + 4 \cdot 11^2}{8 \cdot 11} = 56.51 \, m \quad (6)
\]

Calculation of the speed limit with respect to overturning without lateral inclination:

\[
v_p = \sqrt{\frac{g \cdot a \cdot r_M}{2 \cdot h_T}} = \sqrt{\frac{9.81 \cdot 1.78 \cdot 56.51}{2 \cdot 2.819}} = 13.22 \, m/s^{-1} \quad (7)
\]

Calculation of the speed limit with respect to overturning without lateral inclination:

\[
a_p = \frac{v_p^2}{r_M} = \frac{13.22^2}{56.51} = 3.09 \, m/s^{-2} \quad \Rightarrow \quad k_p = \frac{a_p}{g} = \frac{3.09}{9.81} = 0.31 \quad (8)
\]

Calculation of the speed limit value with respect to shear without lateral inclination:

\[
v_2 = \sqrt{\mu_b \cdot g \cdot r} = \sqrt{0.8 \cdot 9.81 \cdot 56.51} = 21.05 \, m/s^{-1} \quad (9)
\]

**Sample calculation for a right-hand curve village Jablonica (route: Skalica - Trnava)**

The measured values at the maximum lateral acceleration during transport in a given curve are as follows:

- truck speed: 3.25 m.s⁻¹
- gravitational acceleration multiple for lateral acceleration (k): 0.116

Calculation of turning radius using orthophoto map in a given locality:

\[
r_M = \frac{t^2 + 4 \cdot h^2}{8 \cdot h} = \frac{57^2 + 4 \cdot 8^2}{8 \cdot 8} = 54.77 \, m \quad (10)
\]

Calculation of the speed limit with respect to overturning without lateral inclination:

\[
v_p = \sqrt{\frac{g \cdot a \cdot r_M}{2 \cdot h_T}} = \sqrt{\frac{9.81 \cdot 1.78 \cdot 54.77}{2 \cdot 2.819}} = 13.02 \, m/s^{-1} \quad (11)
\]

Calculation of the speed limit with respect to overturning without lateral inclination:

\[
a_p = \frac{v_p^2}{r_M} = \frac{13.2^2}{54.77} = 3.095 \, m/s^{-2} \quad \Rightarrow \quad k_p = \frac{a_p}{g} = \frac{3.095}{9.81} = 0.31 \quad (12)
\]

Calculation of the speed limit value with respect to shear without lateral inclination:

\[
v_2 = \sqrt{\mu_b \cdot g \cdot r} = \sqrt{0.8 \cdot 9.81 \cdot 56.51} = 20.73 \, m/s^{-1} \quad (13)
\]
Table 2. Summary of calculations in selected curve with extreme values on the route from Skalica to Trnava [author]

|                                | Jablonica - left curve | Jablonica - right curve |
|--------------------------------|------------------------|-------------------------|
| **Measured values**            |                        |                         |
| Measured speed [m.s\(^{-1}\)]:| 4.050                  | 3.250                   |
| Measured value of the lateral | 0.133                  | 0.116                   |
| acceleration multiple [m.s\(^{-2}\)]: |                        |                         |
| Radius according to ortho-photo map [m]: | 56.511              | 54.766                  |
| **Riding in a curve**          |                        |                         |
| No inclination                 |                        |                         |
| Limiting speed due to overturning [m.s\(^{-1}\)]: | 13.230             | 13.024                  |
| Limiting lateral acceleration for overturning [m.s\(^{-2}\)]: | 3.097               | 3.097                   |
| Limiting factor of lateral acceleration for overturning [-]: | 0.316              | 0.316                   |
| Limit speed due to skidding [m.s\(^{-1}\)]: | 21.059              | 20.732                  |
| Boundary lateral acceleration to skid [m.s\(^{-1}\)]: | 7.848               | 7.848                   |
| Limiting factor of lateral acceleration per skid [m.s\(^{-1}\)]: | 0.800              | 0.800                   |
| Transverse inclination inwards 5° |                        |                         |
| Limiting speed due to overturning [m.s\(^{-1}\)]: | 15.162             | 14.926                  |
| Limiting lateral acceleration for overturning [m.s\(^{-2}\)]: | 4.068               | 4.068                   |
| Limiting factor of lateral acceleration for overturning [-]: | 0.415              | 0.415                   |
| Limit speed due to skidding [m.s\(^{-1}\)]: | 23.001             | 22.643                  |
| Boundary lateral acceleration to skid [m.s\(^{-1}\)]: | 9.361              | 9.361                   |
| Limiting factor of lateral acceleration per skid [m.s\(^{-1}\)]: | 0.954              | 0.954                   |
| Minimálna rýchlost’ šmyk dovnútra [m.s\(^{-1}\)]: | nonexisting | nonexisting |
| Size of lateral friction coefficient for inward shear at speed \(v_1 = \) 1 m.s\(^{-1}\) (upper cell) \(a v_2 = 2\) m.s\(^{-1}\) [-]: | 0.086              | 0.086                   |
| Limiting factor of lateral acceleration per skid [m.s\(^{-1}\)]: | 0.071              | 0.071                   |
| Transverse inclination out of the curve 5° |                        |                         |
| Limiting speed due to overturning [m.s\(^{-1}\)]: | 11.096             | 10.923                  |
| Limiting lateral acceleration for overturning [m.s\(^{-2}\)]: | 2.179              | 2.179                   |
| Limiting factor of lateral acceleration for overturning [-]: | 0.222              | 0.222                   |
| Limit speed due to skidding [m.s\(^{-1}\)]: | 19.214             | 18.914                  |
| Boundary lateral acceleration to skid [m.s\(^{-1}\)]: | 7                  | 7                       |
| Limiting factor of lateral acceleration per skid [m.s\(^{-1}\)]: | 0.666              | 0.666                   |

Table 2 shows that the following relationship was verified:

\[
\alpha_p = \frac{v_p^2}{r_M} = \frac{g \cdot a \cdot r_M}{2 \cdot h_T} = \frac{g}{2} \cdot \frac{a}{r_M \cdot h_T} = \frac{g \cdot a}{2 \cdot h_T}
\]  
(14)
namely that, at different curve radii, the lateral acceleration due to overturning of the combination has the same value at a given lateral inclination, as it depends only on the gravitational acceleration $g$ (m.s$^{-2}$), the wheelbase $a_{n}$ (m), and the height of the centre of gravity when driving in a curve without transverse inclination. This case also applies to driving in a curve with a transverse slope, but the acceleration value changes the angle of the transverse slope along with the previous variables. This verified that the created calculation model is functional and calculates correctly.

5. Determination of critical points on the measured route Skalica - Trnava

In order to be able to determine the conclusions from the measurements and at the same time meet the idea of the applicability of the measurement outputs in practice, it is necessary to mark the critical points on the individual routes on a map base. The lowest calculated critical value of the transverse acceleration is $0.222 g = 2.179 m.s^{-2}$ when considering the transverse slope of the bend outwards at a $5^\circ$ angle. Due to the size of the recorded values, those that reach a value higher than or equal to half of this critical value, i.e. $0.111 g$, were considered critical points. During the measured transport on the route Skalica - Trnava, the set value was reached by the vehicle at the following places:

- Jablonica left curve 0.113g,
- Jablonica right curve: 0.116g,

The marking of these places in Google maps with a note of the size of the value of the achieved lateral acceleration is shown in Fig. 6.

![Figure 6. Designation of critical points due to transverse acceleration on the route Skalica - Trnava](image)

6. Conclusion

After the overall route analysis, which included the calculation of the vehicle’s centre of gravity, the calculations of the lateral acceleration limits with respect to overturning, and the analysis and determination of critical points and sections on the routes based on the measured values, several facts were found, which directly or indirectly affects the occurrence of these extreme values.

In the analysis of transverse acceleration, it was found that one of the causes of transverse forces on the vehicle during travel is the poor condition of the bridges, more precisely the unevenness of the road in the places of bridge expansion, but also the unevenness of the road on the bridge itself. When driving through such unevenness, the vehicle tends to sway when lateral forces begin to act on it and is more prone to tipping over. One of the other causes of extremes of lateral acceleration when passing a vehicle
around a curve is unevenness on the road. When curving at low speeds, there is a low probability that this factor could affect the overturning of the combination. A critical situation at low speeds could occur due to extreme unevenness on the road and a very high centre of gravity of the vehicle combination. A critical situation is much more likely to occur when cornering with a transverse slope out of the curve when the vehicle will reach a relatively high speed, the centre of gravity will be relatively high and the transverse unevenness (poor technical condition of the road) may cause the vehicle to rock, thus reducing the speed limit (lateral acceleration) required to roll the combination to the side. When the addition of an extreme in a given curve in longitudinal acceleration is added to these parameters (most often braking occurs in a curve according to the measured values), such a curve becomes critical due to the forces acting on the combination and the load and on their tipping sideways.

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