# INVESTIGATION OF VEHICLE STABILITY ON ROAD CURVES IN WINTER CONDITIONS

**Kristina Kemzūraitė, Saugirdas Pukalskas, Gintautas Bureika**

*Vilnius Gediminas Technical University*
*Faculty of Transport Engineering*
*J. Basanavičiaus Street 28, LT-03224 Vilnius, Lithuania*
*tel.: +370 5 2744 789, fax +370 5 2745 068*
*e-mail: kristina.kemzuraite@vgtu.lt, saugirdas.pukalskas@vgtu.lt, gintautas.bureika@vgtu.lt*

***Abstract***

*The paper reveals peculiarities of a vehicle movement/operation on road curves when the road surface is slippery and/or snowy, with asphalt ruts. The survey of scientific works related to the lateral acceleration and movement dynamics of a vehicle is presented. Field experiments with different vehicles were carried out in winter conditions. The acceleration value and stability parameters depending on the speed of a vehicle and adhesion coefficient on road curves are analysed. Dependence of the vehicle lateral acceleration on road curves with various adhesion surfaces are given in graphical charts. Recommendations how to improve road safety by limitation of the speed in winter conditions are formulated. Finally, basic conclusions are given. Handling the vehicle on the road with the compressed snow surface (on the curve of the radius of 120 m) is much more dangerous when the adhesion coefficient of the wheels and the road is low if compared to handling the vehicle along the dry ruts at the same speed. When the vehicle moves along the curve of 120 m radius at a speed of 70 km/h, and the road surface is snowy, the lateral acceleration of 3.1 m/s$^2$ is reached. The paper indicates that lateral acceleration of 3.1 m/s$^2$ can be reached while moving along the snowy road with dry ruts at a speed higher in 27% (90 km/h). For improving the vehicle safety, it is recommended to have road signs on sharp turns/ curves ($R \leq 120$ m) to decrease the vehicle speed in 20 km/h.*

***Keywords:*** *vehicle stability, vehicle dynamics, road curve, road surface adhesion coefficient, lateral acceleration, road traffic safety*

## 1. Introduction

There are many reasons for a vehicle to lose its controllability: unfavourable weather and road conditions, lack of regular vehicle care, maintenance and repair, the driver‘s inexperience, sharp cornering (when passing an obstacle or underestimating a curve). A vehicle will react in a different way when the driver steers smoothly, or when the vehicle slightly declines from the lane. Loss of stability of a vehicle may cause its skidding on the road, or even rollover. While the adhesion to the road surface is sufficient, a skilled driver can manage the vehicle during the first stage of skidding (when skidding can still be controlled). An inexperienced driver may panic when the vehicle starts skidding and it makes it even more complicate to control. This may result in sliding off the road or even rollover. When the vehicle moves straightforward, the acceleration is longitudinal or lateral, and in the curve, both the types of acceleration may occur. In the curve the vehicle increases or decreases its speed, therefore its tilt angles change, as well as the amplitudes of longitudinal and lateral acceleration.

The researchers Prentkovskis and Bogdevicius analysed the vehicle dynamics related to the contact between the wheel and the road surface [1]. A model of the vehicle was made to estimate the motion of the vehicle body, as well as the motion of its front and rear suspension, wheels- and- road contact, wheel locking and changes in the operational drive. The road surface has been analysed with the help of its simulation by finite elements of a triangle. A certain level or road surface roughness, coefficients of road surface- and- wheels adhesion, as well as the position of the wheels of the vehicle in the longitudinal and transversal directions have been noted as the key points of each finite element.

The investigator Kudarauskas made a thorough analysis of the adhesion coefficient [2]. The author emphasises the stability of a vehicle while braking to be the main task while modelling the coefficient of adhesion of the road and wheel-tyres. It is essential to have the most precise mathematical model of adhesion coefficient and evaluate all the factors determining the adhesion between the tyres and the road surface. The model of evaluation of adhesion coefficient must be made in two stages. The first stage is meant for determining the dependence of adhesion coefficient on critical factors. If necessary, the experiment data can be used for the purpose. The influence of the factors must be specified in the second stage, to ensure the minimum discrepancy of the values of mathematical modelling with the data of the experiment.

Hence we may conclude that the elaborated method of expert evaluation can be applied for precise estimation of the vehicle stability and determining the dependence of adhesion coefficient on critical factors. For a more precise estimation, the obtained equation must be supplemented by mathematical models of the critical factors determining the adhesion coefficient.

The scientific paper by Zukas and Sokolovskij [3] analyses various types of a vehicle manoeuvres and the possibilities to apply any of them in relevant situations. In case of emergency the vehicle is usually handled by braking it in order to avoid the unexpected obstacle on the road. The paper includes the schemes to display the tracking of the manoeuvre, and the explanation of the driver's behaviour. The formulas have been given to calculate different parameters during the motion of a vehicle. The authors estimated the efficiency of various types of manoeuvres on the account of different situations.

Authors Vansauskas and Bogdevicius analyse the stability of the vehicle heading along the ruts on the road [4, 5]. The traffic safety depends on many factors. One of them is the road quality. The authors analyse the influence of rut geometry on the vehicle stability. The researchers made a 3D model of the vehicle, as well as the models for the wheel traction and road surface geometry.

The scientist Frankowski analyses the stability of a log-carrying articulated vehicle in his research [6]. The author states the manoeuvre related rollovers are the most important elements of the vehicle lateral stability. This type of rollover may occur at the moment of braking and making sharp steering. However, the most important point that influences the lateral stability is the transverse load distribution coefficient or in other words- dynamic load distribution. The value concerns the loss of road-wheel adhesion. Therefore, it is extremely important to revise and estimate the lateral stability of a vehicle hauling a trailer, analyse the computation methods, estimate the transverse power distribution coefficient.

The researchers Petrovas and Bartulis compare the static stability of dumpers in their scientific work [7]. They also differentiate the static and dynamic stability. Static stability of a vehicle is defined as its balance state affected by the external load unvaried in its size and direction. Computation of static stability gives the possibility to determine the conditions to be met by force systems loading the vehicle. The state of static stability is determined by its long term stability. In case the stability gets unbalanced it will cause a sudden rollover of a vehicle.

Ability of a vehicle to stand maximum load during the rollover determines its marginal stability. The rollover of a vehicle occurs over a certain axis, called rollover axis. The position of rollover axes depends on the construction of a chassis of the vehicle.

Most of scientific works describe the braking and motion dynamics as well as their effectiveness [8, 9].

The stability of heavy goods vehicles (HGV), their manoeuvring and steering on a road are also frequent topics in many research works, as well as vehicle motion in different modes [10-14].

This research analyses the motion of a vehicle during cornering and swerving, as well as redistribution of its transverse forces depending on the speed of the vehicle and cornering radius.

## 2. Theoretic analysis of handling a vehicle while cornering

Sometimes a precondition for slipping is just speeding with no account on the road conditions. If the vehicle is too much speeding and the traction/gravity force is approaching the value of the force of driven wheels adhesion to the road, the slip of the wheels must be eventual.

Maximum safe speed for motion stability is declining when the adhesion coefficient is decreasing and the road surface resistance is increasing while the vehicle is being accelerated. It determines the loss of the direction stability, mostly expected on the road with a rough slippery surface (compressed snow, partly icy asphalt, or bumpy places). Drivers often increase the speed to sweep by the bumpy places on the road. The vehicle motion along the bumpy road requires higher traction force.

If a snowy or icy stretch occurs with low adhesion coefficient, the forces $P_t$ (traction) and $P_{adh}$ (adhesion) may become equal and the driving wheels will start skidding. The skidding is dangerous, because the skidding wheels cannot resist even the low transversal force without the lateral skidding. This is what causes the vehicle skidding.

If the computation shows the traction force is higher than the adhesion force, and the actual speed is lower the speed limit, the driving wheels will not start skidding in the existing weather conditions. The only condition for skidding occurs when the vehicle is speeding at $v_{max.}$ In principle, the vehicle can move at the above mentioned speed for an unlimited period with no loss of transversal stability. Nevertheless, in real conditions there are always interfering forces and moments, ready to change the direction of the vehicle motion. When the speed is low, the impact of interference is usually imperceptible/ indiscernible, but when the speed is high, the loss of stability may occur as well as skidding.

Besides, when the vehicle is reaching its speed close to maximum speed limit, the wheels will cause big change in the contact with the road surface if it runs into a hole or onto a bump; in some cases it may cause abruption of the wheels from the road surface.

There is a certain distance between the wheels of the vehicle, as well as inner and exterior angles during the turn (Fig. 1).

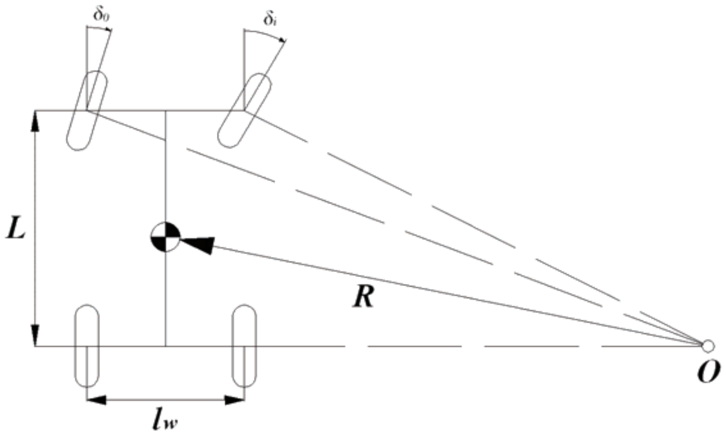


*Fig. 1. Bend geometry: L – vehicle base; $\delta_o$ – turning angle of the front outer wheel ….; $\delta_i$ – turning angle of the front inner wheel; R – radius of road curve; $l_w$ – the distance between the axes*

This is the following formula of the base of the vehicle: $L = l_f + l_r$ ($l_f$ – distance from the vehicle centre of gravity to the front axle, m; $l_r$ – distance from the vehicle centre of gravity to the rear axle, m) the value is low if compared to the radius R. When the skidding angle is low, then:

$$\delta = \frac{L}{R}, \quad (1)$$

where:

$\delta$ - average turning angle of front wheels, degrees,

$L$ - vehicle base, m,

$R$ - radius of road curve, m.

The radius of inner and exterior angles of the wheel turn is different:

$$\delta_0 = \frac{L}{R + \frac{l_w}{2}}, \qquad (2)$$

$$\delta_i = \frac{L}{R - \frac{l_w}{2}}. \qquad (3)$$

The average angle of the turn of front wheels approximately equals:

$$\delta = \frac{\delta_0 + \delta_i}{2} \cong \frac{L}{R}. \qquad (4)$$

The difference between $\delta_i$ is the following:

$$\delta_i - \delta_0 = \frac{L}{R^2} l_w = \delta^2 \frac{l_w}{L}. \qquad (5)$$

Hence, the difference between the twisted angles of the front wheels is directly proportional to the average square of the twisted angle.

## 3. Methods for testing the vehicle dynamics while cornering

Research in lateral acceleration of the vehicle was carried out under the following conditions:

1) two vehicles were tested to make the research: TOYOTA PRIUS (year of production 2005) and VW GOLF (year of production 2007),
2) both the vehicles were in good technical conditions, with the brake system installed in the factory,
3) during the testing, there were two persons inside the vehicle: a driver and a passenger taking down the readings of the measurement device,
4) the tyres of the vehicles were of an appropriate size, recommended for the vehicle model. The tread depth was 3 mm,
5) each vehicle was steered by the same driver,
6) the vehicles in winter tyres (non studded ones) were tested on the compressed snow as well as on the snowy road surface with ruts (the condition was accepted as driving on the dry surface, as the vehicle moved ahead along the ruts),
7) air pressure inside the tyres was appropriate for carrying passengers in each model,
8) testing was performed on a horizontal asphalt road with a curve ranging up to 120 m,
9) the chosen speed was safe on curves and it was steadily increased by 10 km/h.

The measurement was performed with an electronic device XL Meter Pro Gamma (Fig. 2).

*Fig. 2. Measurement device XL Meter Pro Gamma*

The mode of the device was chosen for measuring vehicle's lateral and longitudinal acceleration (deceleration).

## 4. Experimental testing and results

At first the vehicle motion was tested on the curve, when the road surface was snowy with dry ruts on it. The case was determined as the dry road surface/ asphalt in winter conditions, and resulted in the adhesion coefficient of the wheel tyres to the road surface being φ = 0.7. On the curve the speed of a vehicle was 50 km/h with acceleration in every 10 km up to the speed of 90 km/h (Fig. 3). The lateral acceleration varied from 1.1 m/s$^2$ to 3.4 m/s$^2$. The highest value of the lateral acceleration is obtained when the vehicle VW GOLF moves at a speed of 90 km/h on the curve of the radius of 120 m.

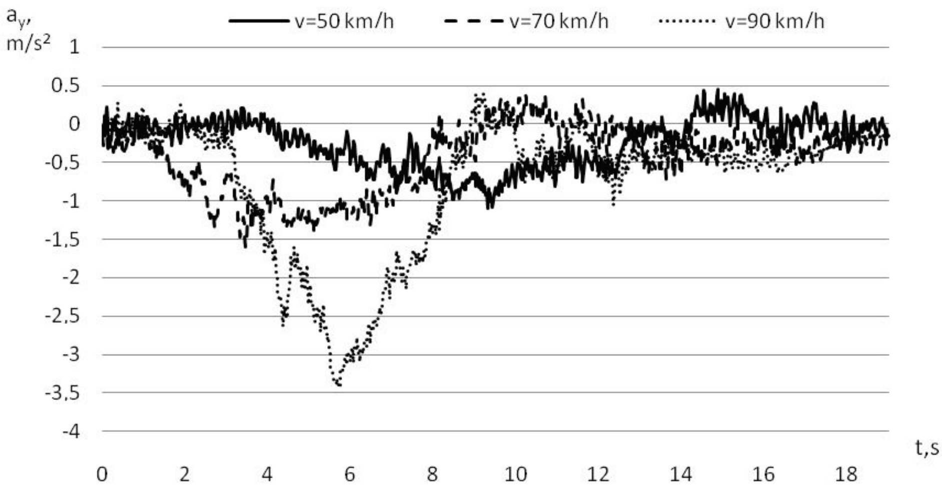


*Fig. 3. Lateral accelerations on snowy road surface with asphalted ruts*

While going along the asphalt road, covered with compressed snow, the adhesion between the road surface and the wheels, i.e. the adhesion coefficient, is φ = 0.2. In this situation, on the same curve (R = 120 m) the vehicle is moving along at a speed ranging from 30 km/h to 70 km/h with the intervals of acceleration by 10 km/h. When the speed *v* is70 km/h on the curve, the skidding occurs, but can be handled yet. The lateral acceleration value increases in approximately up to 3.1 m/s$^2$ (Fig. 4).

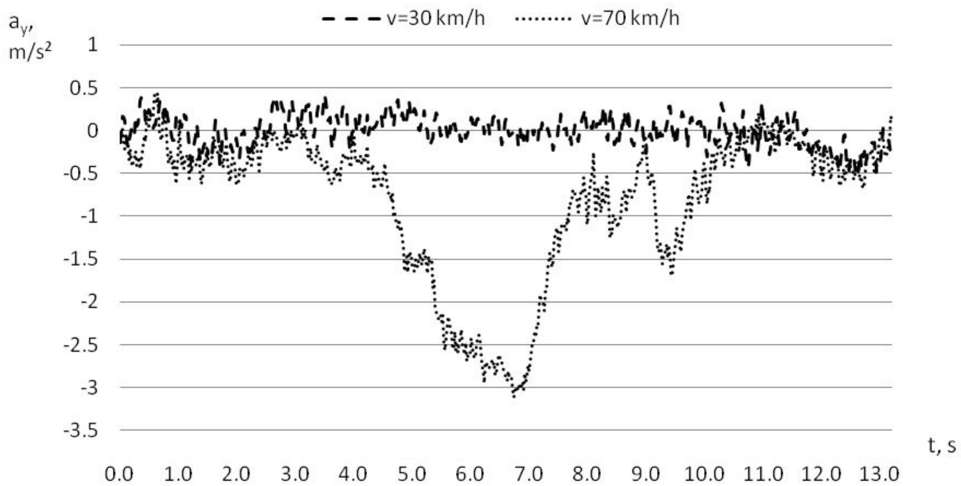


*Fig. 4. Lateral accelerations on snowy road surface*

When the lateral accelerations on the curve are compared during the same speed (v = 70 km/h), but on a different road surface (compressed snow and dry ruts on a snowy road), the following result is obtained, see Fig. 5.

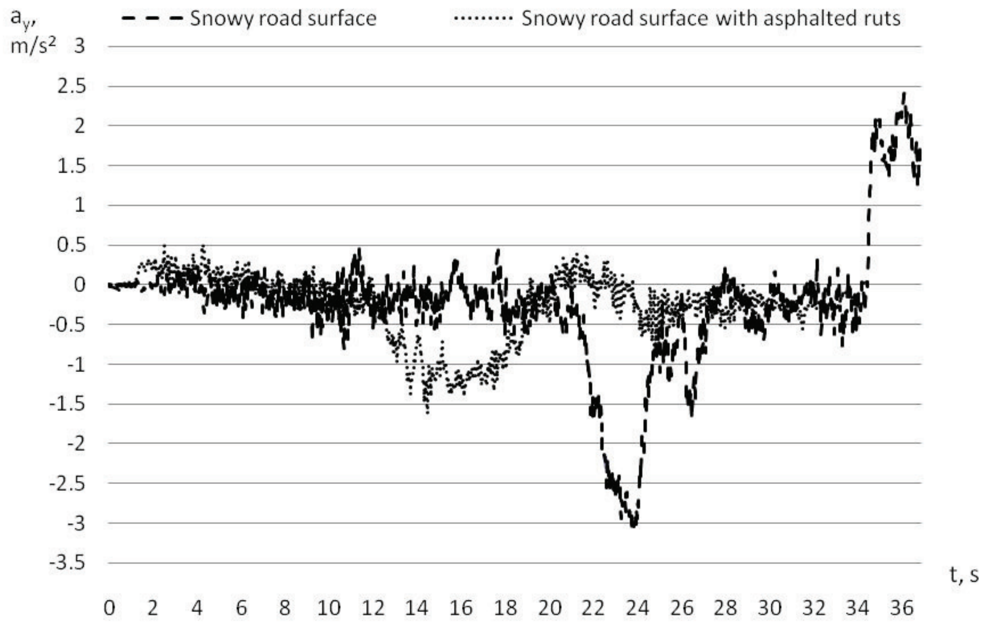


*Fig. 5. Lateral accelerations on different road surfaces (v = 70 km/h)*

Figure 5 displays the increase of the vehicle's lateral acceleration when the vehicle moves along the road covered with the compressed snow in comparison of its motion on the snowy road with dry asphalt ruts. The stability of a vehicle decreases twice and if we keep the speed increasing the vehicle can slip out of road. For increasing the automobile safety on the snowy curves, the speed limit should be decreased.

## 5. Conclusions

1. The obtained results confirm that handling the vehicle on the road with the compressed snow surface (on the curve of the radius of 120 m) is much more dangerous when the adhesion coefficient of the wheels and the road is low ($\varphi$ = 0.2), if compared to handling the vehicle along the dry ruts at the same speed.
2. When the vehicle moves along the curve of 120 m radius at a speed of 70 km/h, and the road surface is snowy, the lateral acceleration of 3.1 m/s$^2$ is reached, while on the snowy surface with dry asphalt ruts the lateral acceleration is approximately 1.6 m/s$^2$ when the vehicle moves at the same speed.
3. The same lateral acceleration (3.1 m/s$^2$) can be reached while moving along the snowy road with dry ruts at a speed higher in 27% (90 km/h).
4. For improving the vehicle safety, it is recommended to have road signs on sharp turns/ curves ($R \leq 120$ m) to decrease the vehicle speed in 20 km/h.

## References

[1] Prentkovskis, O., Bogdevičius, M., *Dynamics of a Motor Vehicle Taking Into Consideration the Interaction of Wheels and Road Pavement Surface*, Transport, 17(6): 244–253, 2002.

[2] Kudarauskas, N., *Influence of the Construction of Car Brakes on Its Stability During Braking*, In Proceedings of the 6th International Scientific Conference Transbaltica-2009, pp. 114-118,

2009.

[3] Žukas, A., Sokolovskij, E., *Įvairių automobilio manevravimo kelių ilgių palyginimas*, Konferencijos Mokslas – Lietuvos ateitis pranešimų rinkinys, Transporto inžinerija: Transporto priemonės ir kelio sąveika, Tom. 1, Nr 6, pp. 10-13, 2009.

[4] Vansauskas, V., Bogdevičius, M., *Investigation into the Stability of Driving an Automobile on the Road Pavement With Ruts*, Transport, 24(2): 170-179, 2009.

[5] Bogdevičius, M., Vansauskas, V., *Dynamic Behaviors of an Automobile on the Road Pavement with Ruts*, Transport Means-2009, Proceedings of the 13th International Conference. ISSN 1822-296X, pp. 5-8, 2009.

[6] Frankowski, J., *Tracking Front Axle Wheels Trajectory by Rear Axle Wheels in an Log-Carrying Articulated Vehicle on a Bend*, Journal of KONES Powertrain and Transpor, 15(4): 139-146, 2008.

[7] Petrovas, D., Bartulis, V., *Savivarčių automobilių statinio stovumo palyginimas*, Dešimtoji Lietuvos jaunųjų mokslininkų konferencija Mokslas – Lietuvos ateitis, Transportas, 1-oji sekcija: Transporto inžinerija: 275-281, 2007.

[8] Przemyslaw, S., Maciej, Z., *Influence of Choice Construction and Exploitations Parameters of Antiterrorism Vehicle of Steering and Stability Border Parameters*, Journal of KONES Powertrain and Transport, 15(4): 517-528, 2008.

[9] Mitunevičius, V., Nagurnas, S., Unarski, J., Wach, W., *Research of Car Braking in Winter Conditions*, Proceedings of the 6th International Scientific Conference Transbaltica-2009, pp. 156-161, 2009.

[10] Prentkovskis, O., Sokolovskij, E., Bartulis, V., *Investigating traffic accidents: a collision of two motor vehicles*, Transport, 25(2): 105-115, 2010.

[11] Sokolovskij, E., Pečeliūnas, R., *The influence of road surface on an automobile's braking characteristics*, Strojniški vestnik, Journal of Mechanical Engineering, 53(4): 216–223, 2007.

[12] Sokolovskij, E., *Automobile braking and traction characteristics on the different road surfaces*, Transport. 22(4): 275-278, 2007.

[13] Sokolovskij, E., Prentkovskis, O., Pečeliūnas, R., Kinderytė-Poškienė, J., *Investigation of automobile wheel impact on the road border*, The Baltic Journal of Road and Bridge Enginering. 2(3): 119-123, 2007.

[14] Kumara, K., Bureika, G., *The Advance Ackerman Steering System of a Full Trailer*, Transport Means-2008, Proceedings of the 12th International Conference, ISSN 1822-296X, pp. 51-54, 2008.