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ANALYSIS OF VEHICLE STABILITY LOSS DUE TO STRONG CROSSWIND GUSTS USING WEB SERVICES IN THE ROUTE PLANNING PROCESS

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Abstract:

Weather conditions play a significant role in road safety. One of its component is a wind influence, which may be affected the moving vehicle from different angles. The final result of such action can take typical kinds of behavior like overturn, slideslip and rotation. Accordingly, vehicles with high side profile are particularly vulnerable to such specific phenomena, what made the planning process more difficult and complex. The article analyses possibilities of a stability loss of a truck vehicle due to strong crosswind gusts. The authors synthesized the model proposed in the literature with available web technologies and the needs of a transport market. Moreover, a method which evaluate a danger of reaching the friction limit by all of the vehicle wheels (slideslip) was developed and is practicable to use. The proposed solution is based on the RESTful API of the weather and web mapping services which allows to collate a direction and a force of wind with a direction of movement and a side profile of the vehicle moving between two locations. What is more a weather forecast is allowed to adopt appropriate variables to compute the air density and evaluate friction coefficients. From the other hand the method uses actual parameters of a vehicle such as axle loads, distance between axles, center of mass location and kind of axle (driven or not). The assumption, which consist in sequencing routes for smaller parts, made it possible to achieve the high accuracy of results on tested areas. The proposed method is simple to implement in any programming language and it can be extended by new functionalities. The analyzed issue can also be a starting point for intelligent systems that can be used in autonomous vehicles.

Keywords: *crosswind, transportation planning, vehicle stability, web applications, route planning*

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1. Introduction

A ubiquity of car accidents comes from a lot of factors like weather conditions (Muslim, Shafaghat, Keyvanfar & Ismail, 2018; Budzyński & Tubis, 2019). This may include phenomena such as fog, rainfalls, snowfalls, hail, blinding sun and strong wind. According to police figures in Poland (Police Report, 2017), strong wind gusts were a cause of 300 road accidents, which resulted in 30 deaths and almost 400 wounded. Statistically 76,6 percent of all road accidents were caused by car drivers, while truck drivers were responsible for 8,1 percent. Generally Heavy - duty vehicles (HDV) are vulnerable to a negative effect of wind gusts, which is forced by the design intent. High value of the drag coefficient is considerable even in the straight-ahead position (Sanda-Mariana, Calin-Vasile & Iacob-Liviu, 2019), but crosswind activity results in a detrimental distribution of forces, especially in oversized trucks with highly located center of mass or a large lateral surface (Macioszek, 2019). Accordingly, an inclusion of weather conditions in the oversized transportation planning process is completely well - founded.
The aim of this article is to elaborate a method based on web technologies which will be used to analyse the possibility of a stability loss on the basis of a direction and a force of wind in relation with a moving vehicle, its velocity, measurements and geographical coordinates between two points of route. Method relies on a theoretical model for which appropriate variables and limitations were adopted (Świderski, Jóźwiak & Jachimowski, 2018). The solution uses a geodetic manner of orienting and calculations arrangement in a coordinate system and a process of downloading up-to-date data from weather services as an input to further calculations. On the basis of obtained results, logical conditions were defined, and as a consequence, a warning method of a potential dangerous incident was developed.

2. Analysis of a stability loss probability

A valid indication of areas with the possibility of strong wind gusts plays a crucial role in road safety. Drivers around the world are alerted to the wind activity by road sings and electric message boards. In Poland, the A-19 sign "*crosswind gusts*" is located next to forests and urban areas entrances/exits, as well as bridges and valleys, where the probability of the strong wind gusts is high. In addition, together with road signs, it is possible to notice a red and white wind indicator, which indicates the direction and force of wind. A wind force generally shall be considered as critical if it exceeds 12 m/s (SEJM RP, 2002).
Automotive companies highlighted that issue and as a result their *crosswind assist* technology is being developed and used in a few types of models e.g., Mercedes Sprinter, Ford Transit. This solution uses Electronic Stability Program (ESP) by active brake intervention on windward side wheels (Daimler, 2019). Introduction of this kind of technologies may be insufficient when vehicle has a large lateral surface or disposition of cargo within the cargo area resulting in elevation of the center of mass. During the test for *Auto Świat* magazine, an artificially created wind gust slided the Mercedes Sprinter approximately 3 meters off course (Auto Świat, 2008). Typical tractor with trailer is characterized by even more lateral surface, which stands at 40m^2 on average for a MEGA trailer. This figure together with a high - located center of mass results in a high susceptibility to a stability loss. Action of lateral force on tyres of driving wheels has an effect on a vehicle behavior through motion trajectory change.
During the analysis of a crosswind influence, taking into account a worst-case scenario is entirely justified. For this purpose, a calculation consisting wind gusts velocity, an altitude range from sea level and a terrain roughness shall be conducted from the relation (PN-EN 1991-1-4:2008):

$$V_W = V_{avg}\left[1 + \frac{2,28}{ln\frac{h}{z_0}}\right] \tag{1}$$

where:
V_W – wind gust velocity,
V_{avg} – average wind velocity,
h – altitude range from sea level,
Z_0 – terrain roughness coefficient.

The terrain roughness coefficient is taken as a general value received from PN-EN 1991-4-4:2008 norm, whereas the altitude range from sea level and the average wind velocity data for random location are acquired using API. Table 1 presents how to determine the relevant roughness coefficient on the basis of description of the special characters divided into categories of the terrain specificity.

Table 1. Value of roughness coefficient Z_0 in relations to terrain type (PN-EN 1991-4-4:2008)

Terrain specificity category		Z_0 [m]
0	Sea, coastal area exposed to the open sea	0,003
I	Lakes or area with negligible vegetation and without obstacles	0,01
II	Area with low vegetation such as grass and isolated obstacles (trees, building) with separations of at least 20 obstacle heights	0,05
III	Area with regular cover of vegetation or building or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0,3
IV	Area in which at least 15% of the surface is covered with buildings and their average height exceeds 15 m	1,0

In view of the fact that 30 percent of the territory of Poland is covered by forests and lowland areas form approximately 75 percent of the entire country, roughness coefficient shall be pessimistic to consider (Lasy Państwowe, 2017). The second terrain category for which above-mentioned parameter equals 0,05 may be used in the analysis of national transportation.
In the literature there are few distinguishing cases of the behavior of a vehicle which underwent a crosswind influence. L. Prochowski described the case where a heavy-duty vehicle moving on linear motion goes automatically to curvilinear motion under the pressure from crosswind activity. In this case the path of the vehicle is calculated from the relation (Prochowski & Kozioł, 2011):

$$R \cong \frac{L}{\mathrm{tg}_{\delta} + (\alpha_2 - \alpha_1)} \qquad (2)$$

where:
R – momentary radius of movement path,
δ – average value of wheels turning angle,
$\alpha_{1,}\alpha_2$ – value of drifting axles (front, rear) angle.

Figure 1 presents three possible movement paths of vehicle's center of mass C moving on linear motion with V velocity, which is affected by resultant force F_Y of wind pressure depending on vehicle dynamic properties. In fact, these characteristics and specificity of shape result in many potential movement paths and three of which were marked as 1, 2 and 3 respectively in Figure 1.
How the vehicle will behave affected by lateral force F_Y depends on the location of three points – vehicle's center of mass, center of crosswind pressure and vehicle's center of side drifting (point where conventional application of lateral force F_Y causes the same angles on wheels of both axles). Proximity of these three points relative to each other reduces the value of resultant wind force and, as a consequence, affecting stability to a lesser extent. In his publications, C. J. Baker identified 3 typical kinds of behavior of a vehicle which underwent a crosswind influence (Baker, 1986):
– overturning,
– sideslip,
– rotation.

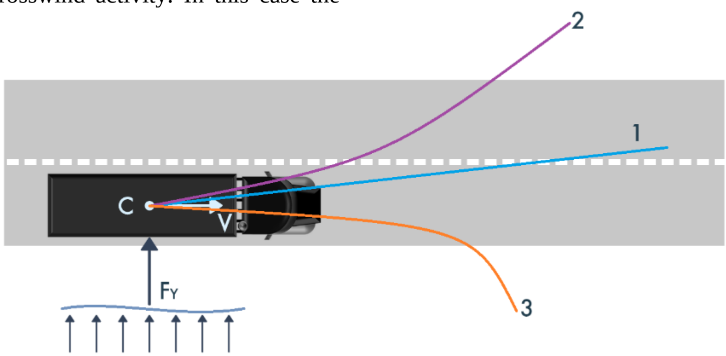

Fig. 1. Possible movement paths of vehicle's center of mass affected by crosswind pressure, where C – center of mass, V – vehicle velocity, F_Y – net force of wind

M. Batista i M. Perkovič specified the following criteria allowing to define the type of vehicle behavior on the basis of the sudden crosswind activity (Batista & Perkovič, 2014):

- the contact force falls to zero,
- all the wheels reach the friction limit,
- a vehicle wheel reaches the friction limit.

In order to determine a critical wind velocity for which occur specified incident, the simplest theoretical model was adopted. The vehicle was considered as a single rigid body with a given mass and dimensions moving on linear motion.

Overturning consist in the lateral tilting of the vehicle, for which contact force on windward wheels reaches zero. In option *rotation* sliding off course occurs due to rotation of vehicle around vertical axis, what was described by L. Prochowski in his publications. Moreover, there is another variant resulting in reaching the critical value of the friction force on all the wheels, which results in shifting the vehicle on the horizontal axis and it is called *slideslip.*

When analysing the vehicle behavior, it is essential to include aerodynamic load coefficients, forces and moments acting on the vehicle related to moving in the medium – ambient air. M. Batista and M. Perkovič identified 3 types of forces and moments acting on the vehicle:

$$F_D = C_D A \frac{\rho V_A^2}{2} \quad F_S = C_S A \frac{\rho V_A^2}{2} \quad F_L = C_L A \frac{\rho V_A^2}{2} \tag{3}$$

$$M_R = C_R A h \frac{\rho V_A^2}{2} \quad M_P = C_P A h \frac{\rho V_A^2}{2} \quad M_Y = C_Y A \frac{\rho V_A^2}{2} \tag{4}$$

where:

$C_D, C_S, C_L, C_R, C_P, C_Y$ – dimensionless quantities of aerodynamic load coefficients,
A – characteristic area of the vehicle,
h – distance between road and vehicle center of mass,
V_A – velocity of apparent wind,
$F_{D,S,L}$ – forces (drag, side, lift),
$M_{R,P,Y}$ – moments (rolling, pitching, yawing),
ρ – air density.

Figure 2 illustrates previously mentioned relations with presentation of forces and moments acting on the vehicle affected by a crosswind activity.

3. Computer warning method of crosswind activity

For the purpose of this article a method was developed, which consists of downloading specific data from the server – value of average (true) wind speed V_{avg}, wind activity direction and coordination of two route points *A* and *B*. This data is possible to acquire from majority of web mapping and weather services providing API (OpenWeatherMap, 2019). Illustrative JSON object type enables to access to the speed parameter of wind expressed in the proper unit e.g., meter/second and angle, which is the azimuth value between the north and direction of wind activity:

{"wind":{"speed":5.1,"deg":150}}.

In order to present an illustrative statement of the moving vehicle in relation to the wind vector, a Geographic Coordinate System was used. Both longitude and latitude values help to draw a straight line containing the axis of the vehicle. The condition for the application, which is based on Euclidean geometry, is proximity of these locations. Actual distance between locations being closer to zero results in higher credibility of measurements. It has to do with the shape of the Earth and averaged the direction of movement between two locations. Access to geographic coordinates and other data through web services like Google Maps is possible by using API requests (Jóźwiak & Betkier, 2018). The responses, which are text-based format of data like JSON allow access to longitude and latitude parameters:

{"coord":{"lon":-122.09,"lat":37.39}}.

Knowing geographical coordinates of two locations allows to compute the azimuth by determining an angle between the north and straight line specified by two points of route (Jagielski, 2005). In order to do that, the function *ATAN2* should be used because of returning the angle between the ray to the point (φ, λ) and the positive *x*-axis (Burger & Burge, 2009). The formula is presented below:

$$\alpha_D = \mathrm{atan2}(\sin\Delta\lambda \cdot \cos\varphi_2, \cos\varphi_1 \cdot \sin\varphi_2 - \sin\varphi_1 \cdot \cos\varphi_2 \cdot \cos\Delta\lambda) \tag{5}$$

where:
φ_1, λ_1 (*latitude, longitude*) – coordinates of first location,
φ_2, λ_2 (*latitude, longitude*) – coordinates of second location.

ATAN2 function returns values between -180º and 180º and shall therefore be normalized to a compass bearing and finally converted to degrees. It is important to remember that calculated bearing (*initial bearing*) might be accepted to considerations only when distance between two points is limited to a few dozen kilometers. Otherwise, it is better to use transformation to receive a *final bearing* (Veness, 2019). To illustrate hypothetical situation author uses explanatory figure. In figure 4 there is a vehicle which has center of mass *C* and is moving between A and B road notes locations. The azimuth of movement direction is taken as α_D angle, in addition, crosswind gust is illustrated as velocity vector V_w and is bounded at *C* point. V_w is calculated from (1) relation and is affecting the vehicle at the angle β_w, but on the other hand, the azimuth of wind direction is taken as α_W. The velocity of the vehicle is presented by V_0 vector and moreover V_P is assigned to head wind, which is the velocity a moving object would experience in still air. V_P vector similarly has oppose head, but the same magnitude and direction relative to V_0 vector. The sum of V_P and V_w is V_A vector, which is determined as apparent wind and, more importantly, its value of magnitude and ψ_w clockwise angle will play an important role in terms of further considerations.

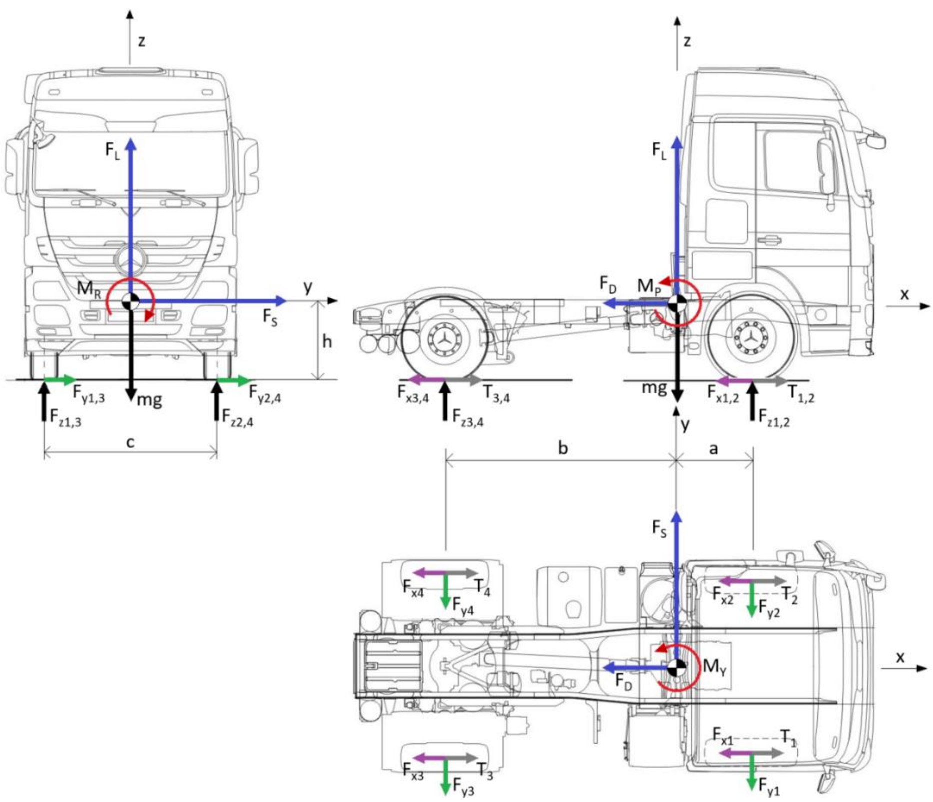

Fig. 2. Dimensions, reaction forces and wind induced resultant forces and moments on the vehicle (Batista & Perkovič, 2014).

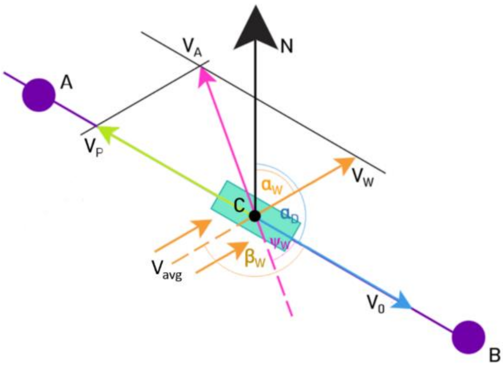

Fig. 4. Visual summary of velocity vectors, angles and azimuths, where C – center of mass, V_0 – vehicle velocity, V_{avg} – average wind velocity, V_A – apparent wind velocity, V_W – wind gust velocity, V_P – head wind velocity, α_W – azimuth of wind gust activity direction, α_D – azimuth of movement direction, ψ_w – yaw angle, β_w – wind affecting angle, A – start location, B – end location

Knowing the azimuth of true wind gust activity direction (α_W) and the movement direction (α_D) allows computing the angle of wind effect on the moving vehicle.

$$\beta_W = 180° - (\alpha_D - \alpha_W) \quad (6)$$

In the present case ψ_w angle is included between direction of vehicle movement and straight line on which the apparent wind vector is located. This angle will determine values of aerodynamic load coefficients and it is possible to compute it from the relation:

$$\psi_w = \arctan\frac{w sin\beta_W}{V_0 + w cos\beta_W} \quad (7)$$

For the purpose of this article the variant of reaching the friction limit by all the vehicle wheels has been followed. This kind of incident occurs when all the vehicle's wheels reaction side forces simultaneously reach its maximal values permitted by friction. The equation takes the form:

$$F_{y1} + F_{y2} + F_{y3} + F_{y4} = \mu_1(F_{z1} + F_{z2}) + \mu_2(F_{z3} + F_{z4}) \quad (8)$$

After using (3) and (4) relations to transform of equation (8), M. Batista and M. Perkovič determined final formula to specify $V_{A,sideslip}$. This value is essential to build warning method for *slideslip* variant and can be calculated from the relation:

$$V_{A,sideslip} = \sqrt{\frac{2mg}{A\rho}\frac{\mu_2 a+\mu_1 b}{[(a+b)C_S+(\mu_2 a+\mu_1 b)C_L+(\mu_1-\mu_2)h(C_D+C_P)]}} \quad (9)$$

where:
a, b – distance from center of mass to individual axles,
m – mass of the vehicle,
g – standard gravity,
h – distance between road and center of mass,
$\mu_{1,2}$ – friction coefficient for axle,
A – characteristic area of the vehicle,
ρ – air density,
C_D, C_S, C_L, C_P – dimensionless quantities of aerodynamic load coefficients.

To calculate the air density for specific location it is necessary to download basic weather parameters from random weather web service with open API. Exemplary JSON object containing required data is presented below:

{"main":{"temp":293.25,"pressure":1019,"humidity":83}}.

The main formula, which determines air density is computed from the relation (NASA, 1976):

$$\rho = \left(\frac{p_d}{R_d \cdot T}\right) + \left(\frac{p_v}{R_v \cdot T}\right) \quad (10)$$

where:
p_d – pressure of dry air,
p_v – water vapor pressure,
T – air temperature,
R_d – specific gas constant for dry air equal to 287,058 [$J/(kg*K)$],
R_v – specific gas constant for water vapor equal to 461,495 [$J/(kg*K)$].

The unknown p_d and p_v pressures are defined by relations:

$$p_v = (6{,}1078 \cdot 10^{\frac{7{,}5T}{T+237.3}}) \cdot RH \quad (11)$$

$$p_d = p - p_v \quad (12)$$

where:

p – total air pressure,
T – air temperature,
RH – relative humidity.

Air density, together with measurements of specific vehicle determines the behavior due to the cross-wind activity. When analyzing trucks with the cargo, each case could be entirely different. Specific position of cargo results in different axle loads and consequently different location of the center of mass. Therefore, the method requires weighting the loaded vehicle by operators. For this purpose, the driver should get on the scale on the front and rear axles separately. Knowing the values of axle loads it is possible to compute distance between axles and the center of mass. Relations (13) present the way of designation of these values (Prochowski & Żuchowski, 2009):

$$a = \frac{Q_2 L}{G} \qquad b = \frac{Q_1 L}{G} \quad (13)$$

where:
Q_1, Q_2 – axle loads,
L – distance between axles,
G – total weight of vehicle.

Determination of the center of mass elevation requires getting a rear axle on the scale and lifting front of the vehicle. The readout of the scale is necessary to derive a proper formula. In addition, the operators should measure the angle of inclination and the radius of wheel. The final formula, which provides the height of center of mass is presented below (Prochowski & Żuchowski, 2009):

$$h = \frac{R \cdot L - G \cdot a}{G \cdot tg_\alpha} + r \quad (14)$$

where:
G – total weight of vehicle,
L – distance between axles,
R – rear axle load (weighted),
a – distance between center of mass and front axle,
α - angle of inclination,
r – radius of wheel.

Another components which describe $V_{A,slideslip}$ velocity are aerodynamic load coefficients. These values are possible to be determined accurately only in the test using a wind tunnel with particular vehicle. C. J. Baker specified these coefficients for high sided road vehicles in terms of angle of wind activity towards direction of movement (Baker, 1986). This is useful in this case, taking into account the fact that the aim of the method is to develop warning system for vehicles, which are vulnerable to strong wind gusts. Table 2 presents generalised values of aerodynamic load coefficients in relation to ψ angle.
It is worth noting that vast majority of high sided transportation vehicles have comparable aerodynamic properties related to similar shape. Accordingly, the assigned values should be helpful in considerations.
The last variable which occurs in formula for limitation speed of apparent wind is friction coefficients depended on a number of variables. Its value will be evaluated differently in order to fact that axle can be driven or not (Batista & Perkovič, 2014).

Table 2. Value of aerodynamic load coefficients in relations to angle of wind activity (Baker, 1988)

	ψ value range			
Coefficients	$0 < \psi < \pi/2$	$\pi/2 < \psi < \pi$	$\pi < \psi < 3\pi/2$	$3\pi/2 < \psi < 2\pi$
ψ'	ψ	$\pi - \psi$	$\psi - \pi$	$2\pi - \psi$
C_S	$5.2\sin\psi'$	$5.2\sin\psi'$	$-5.2\sin\psi'$	$-5.2\sin\psi'$
C_L	$1.1(1 - \cos4\psi')$	$1.1(1 - \cos4\psi')$	$1.1(1 - \cos4\psi')$	$1.1(1 - \cos4\psi')$
C_D	$-0.5(1 + \sin3\psi')$	$0.5(1 + \sin3\psi')$	$0.5(1 + \sin3\psi')$	$-0.5(1 + \sin3\psi')$
C_R	$4.4\sin\psi'$	$4.4\sin\psi'$	$-4.4\sin\psi'$	$-4.4\sin\psi'$
C_P	$-2(1 - \cos2\psi')$	$2(1 - \cos2\psi')$	$2(1 - \cos2\psi')$	$-2(1 - \cos2\psi')$
C_Y	$6\sin^2\psi'$	$6\sin^2\psi'$	$-6\sin^2\psi'$	$-6\sin^2\psi'$

$$\mu_{1,2} = \sqrt{\mu^2 - (i_{1,2}q - f_R)^2} \tag{15}$$

where:
$\mu_{1,2}$ – friction coefficient for axle,
$i_{1,2}$ – binary value depends on type of axle,
q – traction parameter,
μ - static friction coefficient,
f_R – rolling resistance coefficient.

The values i_1 and i_2 take the value 1 (driven) or 0 (not driven). In literature, the friction coefficients depend, among others on type of the road surface. In Poland, the vast majority of roads are covered with asphalt for which E. Habich assumed the rolling resistance coefficient as the value in a range of 0,012 – 0,016 (Habich, 1962). In contrast, the static friction coefficient may be determined using weather service API through simple logical conditions. Where there is a risk of rainfall, μ could remain between 0,7 – 0,8 for asphalt surface, otherwise its value will decrease to 0,3 – 0,4. The traction parameter is defined by formula (16).

$$q = \frac{(a+b)[F_D + f_R(mg - F_L)]}{(i_1 b + i_2 a)(mg - F_L) + (i_2 - i_1)(hF_D + M_P)} \tag{16}$$

The computed V_A value in *slideslip* variant should be compared with the sum of vehicle velocity and average wind (true) velocity. The V_A can be calculated from the relation:

$$V_A^2 = (V_0 + wcos\beta_W)^2 + (wsin\beta_W)^2 \tag{17}$$

The ratio of V_A to $V_{A,sideslip}$ shall be linked to degree of risk associated with losing the adhesion and therefore possibility of specific traffic incident. What is more, the incident may result in the reduction of the degree of road safety or it may affect driving. The proposed way in which the degree of risk is assigned to the value of the ratio is presented in Table 3.
Determination of accurate ratio ranges cannot be determining without additional testing. As long as the ratio is greater than or equal to 1 cause lack of adhesion, but it is hard to know which other ratios would reflect a specific type of incident. The factor determining the degree of risk will always be the harmful effects felt by the driver. Therefore, negative effects should be assigned to the ranges of the ratio, which is possible after carrying out the relevant studies. On their basis it will be possible to evaluate at what speed the driver should move in windy weather conditions to keep the risk level low.

Table 3. Proposed categorization of vehicle behavior based on V_A to $V_{A,sideslip}$ ratio

$\frac{V_A}{V_{A,slideslip}}$	**Degree of risk of an incident threatening traffic safety**	**Description of effects**
≥ 1	**ALERT**	Lack of adhesion, losing control of the vehicle, a high risk of car accident
(0,8 – 1)	**High risk**	Possibility of clear change off course due to wind gusts, a high risk of car accident
(0,6 – 0,8>	**Medium risk**	Wind is becoming a harmful factor for a driver, correction off course under the influence of wind gusts
≤ 0,6	**Low risk**	No noticeable impact on the moving vehicle

4. Conclusions

The method described in the article has the objective to develop universal solution based on real-time data. This approach results in detailed analysis of travel route in terms of wind activity. The extensive computation capabilities and efficient programming languages offer opportunities to split the route to many parts and analyse each of them using HTTP requests. Moreover, web weather services offer even 16 - day forecasts, so the method can be a useful tool in the transportation planning process. Application of the method would allow to set an optimal date and route to move the load or support the tracking of vehicles during transit. The proposed assumptions can be modified depending on the type of road incident in order to avoid undesirable effects of crosswind. The multitude of variables which are used by author causes possibility to implement the solution in many web route generators. Testing the method indicated that, V_A to $V_{A,\ slideslip}$ ratio generally not exceeding 0.8, even under the hurricane wind for Mercedes Sprinter, which moves at a speed not exceeding 50 km/h. It should be noted that reaching the friction limit on all of wheels is a restrictive assumption and there are a lot of different vehicles with a much higher lateral surface or higher situated center of mass. Moreover, the method may be modelled for an only one wheel, which can reach the friction limit, what is an easier assumption to fulfil and implies an increasing the frequency of alerts. On the other hand, it would have to be determined how specific ranges of ratios would affect the way of driving the vehicle. Despite the fact the method contains a wide range of variables, it is based on a simple static model. Knowledge of accurate aerodynamic load coefficients for specific vehicle models or combinations of vehicles like truck and trailer connection, would affect accuracy of the suggested formula. For this purpose, coefficients should be obtained from producers or gained from the examination in a wind tunnel. The next issue is a behavior of the wind in a complex terrain. This issue has already been raised in literature (Letson, Barthelmie, Hu & Pryor, 2019), however it remains not fully understood. Consequently, a precise analysis would require making measurements in minimum distance of proximity to planned route, while also taking into consideration the infrastructure elements, such as acoustic screens or parts of road construction, such as slopes and ditches. In addition, it would be worth considering possibilities of determination of friction coefficients with reference to the likelihood of precipitation in a specific location and how to formulate calculating functions to remain useful tool in the planning process.

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