Continuous monitoring the vehicle dynamics and driver behavior using navigation systems

George Ene
Claim Expert Coordinator, Bucharest, RO
ene_george@yahoo.com

Abstract: In all fields cost is very important and the increasing amount of data that are needed for active safety systems, like ADAS, lead to implementation of some complex and powerful unit for processing raw data. In this manner is necessary a cost-effective method to estimate the maximum available tire road friction during acceleration and braking by continuous monitoring the vehicle dynamics and driver behavior. The method is based on the hypothesis that short acceleration and braking periods can indicate vehicle dynamics, and thus the available tire road friction coefficient, and also human behavior and his limits. Support for this hypothesis is found in the literature and is supported by the result of experiments conducted under different conditions and seasons.

1. Objective

Developing a system that continuous monitoring the vehicle dynamics and driver behavior, and thus the quality and tire grip level of the road surface, without stereo cameras, adaptive suspension or other expensive sensors. Using verified algorithms and raw data taken from navigation systems it can be determined the level of road roughness and road friction, which means that we would predict how easily a vehicle will skid on a road. For a given wheel, the normalized traction force, $\mu$, is:

$$\mu = \sqrt{\frac{F_x^2 + F_z^2}{N_z}}$$

(1)

When a vehicle of mass $m$ has the same $\mu_{max}$ at all four of its tires, and we consider only longitudinal motion, so the side force $F_y$ can be neglected, the largest longitudinal acceleration $|a|_{max}$ it can achieve, neglecting all resistances, is:

$$|a|_{max} = \max\left|\frac{F_{x1} + F_{x2}}{m}\right| \leq \mu_{max} \cdot g$$

(2)

Where $F_{xi}$ is the longitudinal force at the $xi$ wheel and $g$ is the gravitational constant. Thus, an estimate of $|a|_{max}$ gives us an upper bound on the acceleration, in $g$’s, that a vehicle can achieve. Note that vertical load will contribute to different contact patch area and tire deformation. In all studies vertical wheel load input are kept constant, which in real driving conditions it varies[8].
2. Applications

Anyone who uses a computer, tablet or even a smartphone will no doubt have faced informations from GPS system provided in vehicle by the infotainment systems. Results from collected informations can be used in over-the-air services, with great functionality for autonomous vehicle in the future and no matter how many levels of security a system might have, can inform drivers, machines or people of dangerous conditions, so that they can change their driving speed or style to prevent dangerous emergency situations [1] [2]. Blending the navigation systems with active safety features have serious advantages because there is a lot of high-speed processing going on the vehicle computers and active-safety domain which includes the vehicle’s radar, LiDAR, vision systems, driver-state monitoring and various related sensors and actuators.

3. Methodology. Acquiring and processing data.

The vehicle used is a front wheel drive with standard ABS, without traction or stability control unit, and it was equipped with Velocity BOX, VBOX, and PerformanceBox from Racelogic Ltd. The Racelogic VBOX, and PerformanceBox, is a family of data acquisition devices which is used by the majority of Car Manufacturers, Tyre Manufacturers and car magazines around the world to assess performance. Because it is very easy to edit the test ranges, is a very powerful tool for use in many different kinds of vehicle testing.

![Image of Instruments](image)

**Figure 1. Instruments used for acquiring data**

| **Velocity** | **Distance** |
|--------------|--------------|
| • Accuracy: 0.1 Km/h | • Accuracy: 0.05%(<50cm per Km) |
| • Units: Km/h or Mph | • Units: Km/h or Mph |
| • Update rate: 20 Hz | • Update rate: 20 Hz |
| • Minimum velocity: 0.1 Km/h | • Resolution: 0.05 cm |
| • Maximum velocity: 1800 km/h | • 2D Position: ±5m 95% CEP * |
| • Resolution: 0.01 Km/h | • Height: 5 Metres 95% CEP * |

| **Acceleration** | **Heading** |
|------------------|-------------|
| • Accuracy: 0.5 % | • Resolution: 0.01° s |
| • Maximum: 4 G   | • Accuracy: ±0.2° s |
| • Resolution: 0.01 G |                     |

| **Memory** | **Environmental and Physical** |
|------------|---------------------------------|
| • Type SD Card | • Weight 130 grams |
| • Recording time Dependent on card capacity* | • Size 104.5 mm x 72.8 mm x 25.1 mm |
|                     | • Operating temperature -20 °C to +50°C |
|                     | • Storage temperature -30°C to +80°C |

**Table 1. VBOX Sport Specification**
The data acquisition system is based on GPS 20Hz sensor, that offers very precise position and velocity information. For a GPS receiver, the position as latitude and longitude coordinates are required to plot the vehicle’s path, and the heading is necessary to calculate lateral acceleration. The calculated acceleration values are affected by GPS positioning errors and low sampling rate. In case of longitudinal acceleration, the positioning information is not used, only speed and time, which are very accurate.

One of the test track is presented in figure 2, as it is in a Google Earth environment, with highlighted road and red line for the sample track.

![Test track shown in Google Earth](image)

**Figure 2.** Test track shown in Google Earth

The raw data for velocity and longitudinal with lateral accelerations, obtained from VBOX and GPS receiver is presented in figure 3, for the same recorded track. The values used for these diagrams are not filtered.

![Velocity, longitudinal and lateral acceleration presented as raw data](image)

**Figure 3.** Velocity, longitudinal and lateral acceleration presented as raw data

The PerformanceTools software allows to view the driving data recorded by VBOX file. The software also allows you to display available channels, such as velocity, lateral acceleration, longitudinal acceleration, heading, height, satellites number, yaw rate, latitude, longitude, brake trigger, UTC Time, distance, time, radius of turn results, and to carry out detailed analysis of driver and vehicle performance. The value of velocity, presented in figure 3, is smooth enough but it is obvious that the values used to generate longitudinal and lateral acceleration, presented in the same graph need to be filtered [9] [10]. The software developer of VBOX indicates that smoothing level can be applied to each channel individually and is useful when displaying acceleration channels. Note that the Smoothing Level should therefore be carefully applied, too little and the data can be too ‘noisy’ for easy analysis and too much and valuable information can be lost.
4. Quantification of skill, rule and knowledge-based behavior in road traffic

Human and technical features of the road traffic system combined with their interactive compatibility influence primary safety and accident prevention potential. The enormous kinetic energy involved in the dynamic process of driving is coupled with danger of loss control. Such modeling approaches for human driver behavior in road traffic represent challenges for driver assistance systems [4]. The gaps between human performance limitations and physico-technical constraints of vehicle, road and traffic environment characteristics open up the most promising realms for the development of driver assistance systems. The quantification of skill, rule, and knowledge-based behavior in road traffic was intensified by initiating empirical acquisition of driving behavior data. The g-g diagram, longitudinal versus lateral accelerations, serve as an example to explain this approach. This diagram shows the range of longitudinal versus lateral accelerations at some drivers with average experience, applied during test runs on winding country roads and highways in everyday traffic [3]. The circumferential line present an 85 percentile line, all drivers remain below this outline in 85% of the test driving time, the rule-based range reaches up to the 95th percentile, and all driving states beyond this 95-percentile outline can be looked at as rare events and belong to the knowledge-based behavioral level.

Figure 4. The g-g diagram of normally experienced drivers

Figure 5. Driving behavior collectives compared to adhesion limit circles (differently skilled drivers, road surfaces with high and low friction potentials)

The empirical results at hand show consistently that drivers behavior collectives in traffic on public roads usually remain well below tire adhesion limits as long as the pavement is dry. Thus it may happen that even a cautious driver will exceed the limit of adhesion and hence the risk of accidents will grow considerably. Selecting the G-Circle produces a plot of the Longitudinal vs Latitudinal Acceleration data. Plotting out your own G-circle lets you know if you are exploiting your tire’s true potential. Ideally is a symmetrical plot, but the vehicle almost always generate more G under braking than acceleration, so the accelerating area will be shallower than the breaking part of the circle. All the experiments were performed under different conditions, in all four seasons with different tire types, in different road and atmospheric conditions.

The highly complex nature of many real-world conditions, though, often means that inventing specialized algorithms that will solve them perfectly every time is impractical, if not impossible. But a specially developed algorithm, like Machine Learning, detects the typical features for many different road conditions or driver behavior and this will always be a case with real-world data. Using that kind of algorithms to reach an accurate conclusion, involves many random samples as training data.
Figure 6. Presenting samples during warm weather with dry pavement and summer tires

Figure 7. Presenting samples during cold weather with wet pavement and summer tires

Figure 8. Presenting samples during cold weather with wet and right pavement and winter tires

Figure 9. Presenting samples during cold weather with snow and ice pavement and winter tires
5. Prediction capability and different approaches to estimate the $\mu_{\text{max}}$

This paper evaluates the dynamic capability of the vehicle during acceleration or braking. In the normal driving conditions there is more acceleration then deceleration process, in this case the system can evaluate the vehicle dynamic capabilities and driving behavior, not just information from tire or road conditions. Numerous vehicle parameters cause that an estimator for $\mu_{\text{max}}$ to be a hard operation, and finally $\mu_{\text{max}}$ to be an uncertain value. The parameters that need to take in account classifies as vehicle parameters like velocity, camber angle and wheel load; tire parameters like material, tire type, tread depth and inflation pressure; road conditions like water, snow, ice films depth, temperatures; road parameters like road type, micro and macro geometry, drainage capacity. All these multiple parameters need to take in account for a system that estimate the $\mu_{\text{max}}$.

5.1. Correlation method

The friction coefficient, $\mu$, at a tire is related to the acceleration or deceleration obtained by the vehicle, implicitly to vehicle capacity for traction and braking maneuvers. Extensive testing on different road surfaces with different types of tires shows that this method can develop estimated values for $g_{\text{max}}$ at braking using values of $g_{\text{max}}$ at acceleration, and also allows for classification of roads as either dry, wet, snowy or icy. By using the raw data, acceleration and deceleration, $g$, from different traction and braking maneuvers taken from on a variety of road conditions and surfaces, it demonstrated that it is a direct correlation between $g_{\text{max}}$ at acceleration and $g_{\text{max}}$ at deceleration obtained with same type of road and tire condition.

Surfaces with lower friction coefficient generate low $g_{\text{max}}$ at traction maneuvers and also low $g_{\text{max}}$ at braking maneuvers, for example on icy road if the vehicle generate 0.15g on traction period can also generate 0.3g on braking period, on summer dry road if the vehicle generate 0.45g on traction period can also generate 1.1g on braking period and so on examples can continue on other road and tire types. In figure 10 and 11 it is presented the model and the samples that sustain that observation.

![Figure 10](image-url)

**Figure 10.** The reproduced model for this direct correlation, using the raw data from different traction and braking maneuvers taken from on a variety of road conditions and surfaces.
Dry pavement and summer tires

Wet pavement and summer tires

Dry pavement and winter tires

Snow with ice pavement and winter tires

Figure 11. Samples from different traction and braking manoeuvres taken from a variety of road conditions and surfaces.
5.2. Identification method

With Matlab application, toolbox System Identification, we can approximate the acceleration and deceleration curve using the regression model. Another approach to estimate the vehicle dynamics is to collect raw data and then to use this data to estimate the entire nonlinear curve [5]. Determining $\mu_{\text{max}}$ is then facile because it is the maximum or minimum for braking or acceleration of this estimated curve. Experimental research with vehicles also has the role of obtaining the necessary data to establish mathematical models of their dynamics. Establishing mathematical models based on experimental data is the object of system identification. In present, a mathematical model is often theoretically prefigured and finalized based on experimental data.

![Figure 12](image1.png)

**Figure 12.** Samples data with inputs and outputs signals and different identification method, a) samples data, b) input and output signals, c) continuous-time identification, d) nonlinear identification.

Because experimental data is a discrete series, it is advisable to establish a discrete model and then a continuous model. To obtain a very low error value, which ensures high precision of modeling, it is required to use nonlinear identification with multiple regressors. As can be seen from the discrete model expressions, for example, the relation (5) it is a autoregression, in this case with current regression k to k-10. Due to this fact, which makes the discrete model memory (taking into account regressors before the current one), a very high accuracy is obtained, even if the model is linear.

$$A(q)y(t) = \frac{B(q)}{F(q)}u(t - nk) + \frac{C(q)}{D(q)}e(t)$$

(3)

The limitation encountered to identify the mathematical models of vehicle dynamics, especially dynamic capabilities, is the high number of regressors which involves a powerful and complex program, therefore a delayed estimation about vehicle dynamic, then is needed a different approach.
5.3. Slope method

Another approach to monitor the vehicle dynamics is to find the slope of a linear curves during traction or braking manoeuvres and find the difference between the slopes of acceleration or deceleration curves on different road surfaces. Using the linear identification for traction or braking curves, it can be estimated the slope curves for different road surfaces [8].

The slope angle \( \theta \) is the vertical angle formed by the inclined distance \( \Delta y \) with its horizontal projection \( \Delta x \). If the angle \( \theta \) is positive, vehicle is on the accelerating process, and if it is negative, vehicle is on the braking process. The slope, \( m \), and the slope angle is define by:

\[
\theta = \arctan\left(\frac{\Delta y}{\Delta x}\right)
\]

The slope angle is direct correlated with the parameters of polynomial equation. Using Mathlab, toolbox Curve Fitting, one-degree polynomial equations can be obtained, \( f(x) = p_1 \cdot x + p_2 \), with parameters that have 95% confidence bounds.

\[
y = 11.31 \cdot x - 9.255 \cdot e^5
\]

\[
y = 3.783 \cdot x - 3.208 \cdot e^5
\]

\[
y = -29.15 \cdot x + 2.38 \cdot e^6
\]

\[
y = -8.593 \cdot x + 7.291 \cdot e^5
\]

Figure 13. Representation of slope angle (a) and orientation (b)

Figure 14. Representation of slope characteristics on acceleration and braking process

The experimental results provide the fact that it is a difference between the slopes of slip curves on wet and dry surface. The results obtained following the processing of experimental data show that the polynomial parameter represented the slope curve is higher on dry road and falls on wet or icy road. The slope method using the linear curve is viable indicator if the data points are grouped along on an axis.
6. Conclusions

Relatively low amount of data to process may be an asset for many other researching methods to detect the driver and vehicle dynamics with available friction coefficient as an interaction between tires and the road surface in a proactive way and to use this information to make their vehicles safer. For example, the file presented in figure 3, have 1.19mb with more than 720 seconds of record, involving less than 2.5kb/s to process. By connecting vehicle to a cloud service, road data can be distributed to other vehicles, enabling drivers to adapt their driving style or change routes as they receive information about upcoming hazards or dangerous situations. This cloud data will then be possible to share with other drivers, road authorities and systems for Advanced Driver Assistance or for real time weather navigation data [6] [7].

Analyzing $g$-$g$ diagrams for multiple subjects or teams formed by human-machine, vehicle and software developers can create maps with human performance limitations and physico-technical constraints of vehicle.

Using various cost-effective methods, particularly correlation and slope method, to estimate adhesion limits can enhance prediction capabilities of autonomous vehicles.

Major problems for navigation systems represent reception interference like gaps in reception and multipath reception, and one of the solutions to counter this problems is to work in parallel with other data from CAN vehicle.

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