Assessment of using GPS receivers and INS devices to test the dynamic performances of vehicles

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Abstract

The paper presents the results of an experiment conducted in order to evaluate how different data acquisition devices, based on GPS receivers and/or inertial sensors, can be used in the study of vehicle's dynamics performances. The measured and calculated parameters include velocity, longitudinal and lateral acceleration, slip angle, yaw rate, turning radius. The results obtained with different devices and tools used are then compared in order to identify the most appropriate tools and methods for each case.

Zusammenfassung

In diesem Artikel werden die Ergebnisse von verschiedenen Versuchen vorgestellt, um zu prüfen wie die Daten verschiedener GPS und/oder inertialsensorgestützter Messergeräte zur Beurteilung der Fahrzdynamik von Fahrzeugen verwendet werden können. Die gemessenen und berechneten Parameter enthalten Geschwindigkeit, Längs- und Querbeschleunigung, Gier- und Kurswinkel, Giergeschwindigkeit sowie den Wendekreisdurchmesser. Die Ergebnisse basierend auf den Messungen der verschiedenen Messgeräte und Werkzeuge werden anschliessend verglichen, um für die jeweilige Anwendung das beste Verfahren zu identifizieren.

Introduction

During the last years, many researchers have developed algorithms for combining GPS data with inertial measurement units (IMU). An approach is using a vehicle motion model in combination with a Kalman filter, to estimate vehicle states when noisy GPS and IMU data are available. There are also studies that extend the GPS/IMU sensor fusion to include dead reckoning through the OBD speed data [1], so that good estimation (including vehicle trajectory) can be obtained using a low cost GPS, IMU and OBD scan tool.

Many studies (as those presented in [2], [3], [4] and [5]) use GPS units (with single or dual antenna) in combination with inertial sensors, and the principles are presented in detail in [3]. Using the PPP (precise-point-positioning) technology it is possible to obtain a higher accuracy of GPS measurements [6].

The values that can be measured directly using GPS and IMU sensors are:

- measured with GPS receivers: position (latitude, longitude), speed, course;
- measured with IMU (inertial) devices: yaw, yaw rate, longitudinal acceleration, lateral acceleration and others.

The values that can be calculated (based on GPS measurements) include:

- longitudinal acceleration, lateral acceleration, radius of turn (and center of turn), yaw rate.

Yaw rate can be measured with a gyroscope, but for vehicle sideslip measurements the ground speed of different points of the vehicle is required, with a good accuracy. The sideslip can be measured directly with a two-antenna GPS system [2], combined if possible with IMU (Inertial Measurement Unit) sensors.

The single-track vehicle model

One of the most frequently used models for the study of the lateral dynamics of a vehicle is the single-track vehicle model, known also as the "bicycle model" [7], [8] (Fig. 1). Both front wheels are represented by one single wheel at point A, and both rear wheels are represented by one central rear wheel at point B.

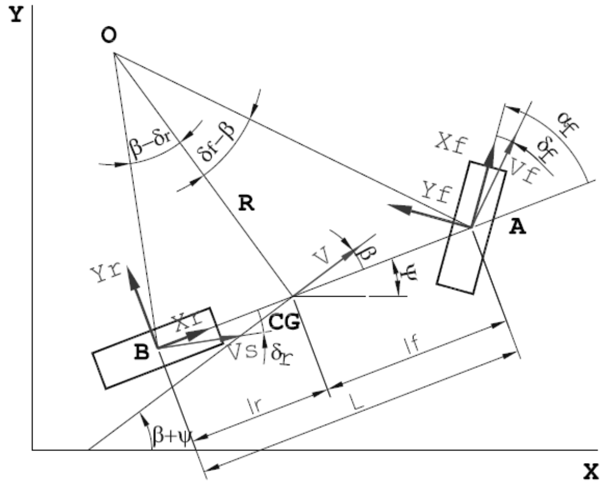

Fig. 1. Simplified model for study of vehicle kinematics [8]

The notation in the figure are as follows:

- the steering angles for the front and rear wheels: δ_f and δ_r;

- the center of gravity of the vehicle is at point CG;

- the distances of points A and B from the CG of the vehicle are l_f and l_r.;

- the wheelbase of the vehicle is L = l_f + l_r.;

- X, Y are inertial coordinates describing the location of the CG;

- Ψ is the the yaw angle and indicates the orientation of the vehicle (heading);

- the velocity at the CG of the vehicle is V and makes an angle β with the longitudinal axis of the vehicle.

The angle β is called the slip angle of the vehicle.

As per Fig. 1, (also presented in [9]) the following equations can be deducted:

$$\frac{\sin(\delta_f - \beta)}{l_f} = \frac{\sin(\frac{\pi}{2} - \delta_f)}{R} \quad (1)$$

$$\frac{\sin(\beta - \delta_r)}{l_r} = \frac{\sin(\frac{\pi}{2} + \delta r)}{R} \quad (2)$$

The rate of change of the vehicle heading (the yaw rate of the vehicle body) is:

$$\dot{\Psi} = \frac{v}{R} \quad (3)$$

and the overall equations of motion will be [1], [8]:

$$\dot{X} = v \cdot \cos(\Psi + \beta) \quad (4)$$

$$\dot{Y} = v \cdot \sin(\Psi + \beta) \quad (5)$$

$$\dot{\Psi} = \frac{v \cdot \cos(\beta)}{l_f + l_r}\left(\tan(\delta_f) - \tan(\delta_r)\right) \quad (6)$$

Some of the variables on these equations can be measured and are input data, others will be calculated. Which values are measured and which are calculated depends on the measuring devices used.

Experimental data - acquiring and processing

The test track is presented in Fig. 2. The vehicle driven on this track was instrumented with various sensors (Fig. 3), including Speedbox [10], DS-5 [11] and PIC-DAQ [12].

Speedbox [10] is a high precision automotive speed sensor that uses inertial (IMU) and GPS technology for accurate and robust measurement of vehicle performance. The system used has a dual GPS RTK (real time kinematics) antenna layout. The INS option uses complex algorithms and Kalman filtering to cross reference the GPS data with the inertial data. As it is stated on the manufacturer's website, "this makes it ideal for real world road testing as well as test tracks".

DS-5 [11] is an in-house built data acquisition system, based on the GPS 18x-5Hz from Garmin, a sensor that offers very precise position and velocity information [13]. Data are sent to a computer as NMEA 0183 sequences, where they are logged as text files, using a custom developed software. For this experiment two sensors were used, mounted at front and rear of the vehicle's roof. Each sensor sends its own speed and heading information to the logger, and these are then used to compute the accelerations, yaw and slip of the vehicle.

PIC-DAQ [12] is a data acquisition platform that records dynamic data, where accelerations and angular velocities describe the movement. It is used for the evaluation of the vehicle driving performance, braking tests, and vehicle crash tests. It uses three axial acceleration and angular velocity sensors for measurements.

Fig. 2. Test track, recorded with GPS receiver and shown in Google Earth

Fig. 3. Instrumented vehicle

A part of a test conducted on the track is presented in Fig. 4, based on the position information recorded with the two DS-5 receivers.

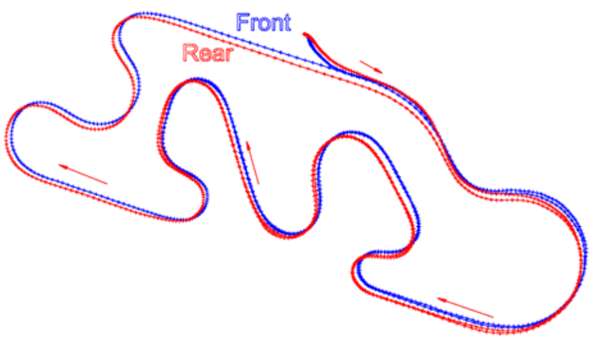

Fig. 4. Test track (recorded with two GPS receivers)

For each GPS receiver, the position as latitude and longitude coordinates is known. These coordinates are transformed to carthesian coordinates and from three consecutive points, using the equation of a circle described by three points, the radius of turn can be calculated, and also the center of the turn. The lateral acceleration is then calculated as:

$$acc_y = v^2/R \quad (7)$$

where acc_y is the lateral acceleration, v is the measured speed and R the calculated radius of turn. Lateral accelerations obtained for both GPS antennas, placed in front and rear of the roof, are given in Fig. 5. There are some small differences between the two curves, caused also by the different speed of the antennas (because of the lateral movements of the vehicle body).

The longitudinal acceleration is easy calculated as

$$acc_x = dv/dt \quad (8)$$

where acc_x is the longitudinal acceleration, v is the measured speed and t is the time given also by the GPS receiver.

In Fig. 6 is presented the diagram of lateral acceleration measured with inertial sensor (accelerometer). Data for both Fig. 5 and Fig. 6 are filtered using a Kalman filter.

A Kalman filter is comprised of a measurement update and a time update [14]. The filter model [15] assumes that the state of a system at time t evolved from the prior state (at time t-1), as described by the equation:

$$x_t = F_t x_{t-1} + B_t u_t + w_t \quad (9)$$

where x_t is the state vector containing the terms of interest (e.g. acceleration) at time t, u_t is the vector containing any control inputs, F_t is the state transition matrix which applies the effect of each state parameter at time t-1 on the state at time t, B_t is the control input matrix which applies the effect of each control input parameter in the vector u_t on the state vector, and w_t is the vector containing the process noise terms for each parameter in the state vector.

Having also measurements on the system, these measurements can be expressed as:

$$z_t = H_t x_t + v_t \quad (10)$$

where z_t is the vector of measurements, H_t is the transformation matrix that maps the state vector parameters into the measurement domain, and v_t is the vector containing the measurement noise terms for each observation in the measurement vector. The measured value is a linear combination of the signal value and the measurement noise

The value of x_t is a linear combination of its previous value plus a control signal u_t and a process noise. We can assume that in case of many measurements there is no control signal (e.g. the cases when we measure only the speed using GPS devices or only the acceleration using accelerometers).

The algorithm of the discrete Kalman filter includes a time update and a measurement update [16]. Eventually the equation of the filter can have a simplified form:

$$\hat{x}_t = k_t \cdot z_t + (1 - k_t) \cdot \hat{x}_{t-1} \qquad (11)$$

where $\hat{x}_t$ is the current estimation of the variable and $\hat{x}_{t-1}$ is the previous estimation of the analysed variable; z_t is the measured value and k_t is the Kalman gain, which is also updated at each iteration.

The operation of filtering add a small delay, and when the sampling rate is different the delay will be also different, as can be seen in Fig. 7, where all diagrams (for the three different aquisition systems) are overlapped.

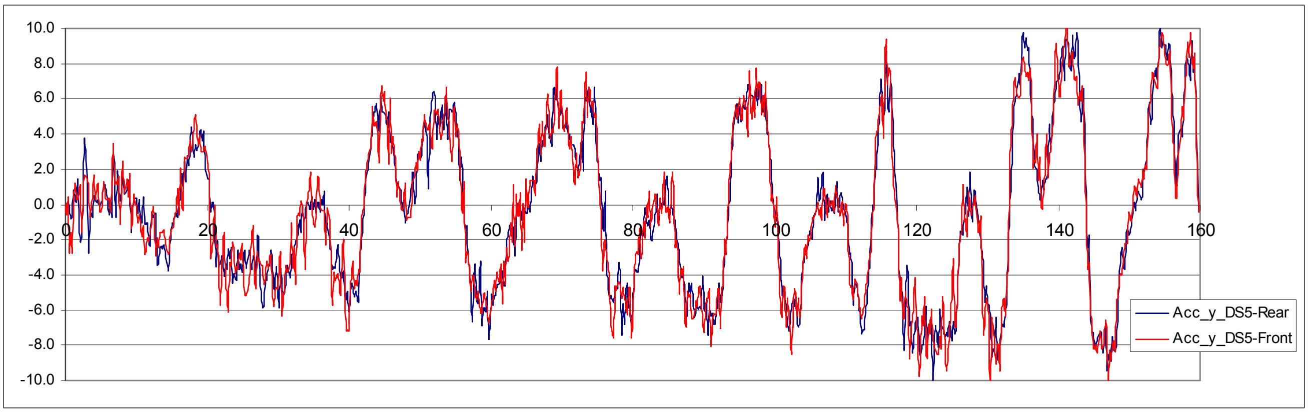

Fig. 5. Lateral accelerations (from two independent GPS receivers, mounted in front and rear of the vehicle roof)

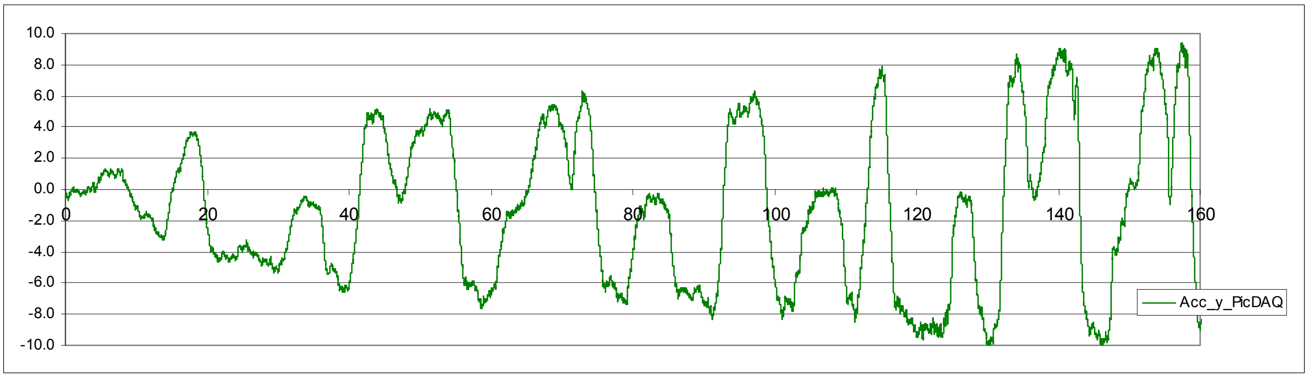

Fig. 6. Lateral accelerations (from inertial unit - PicDAQ)

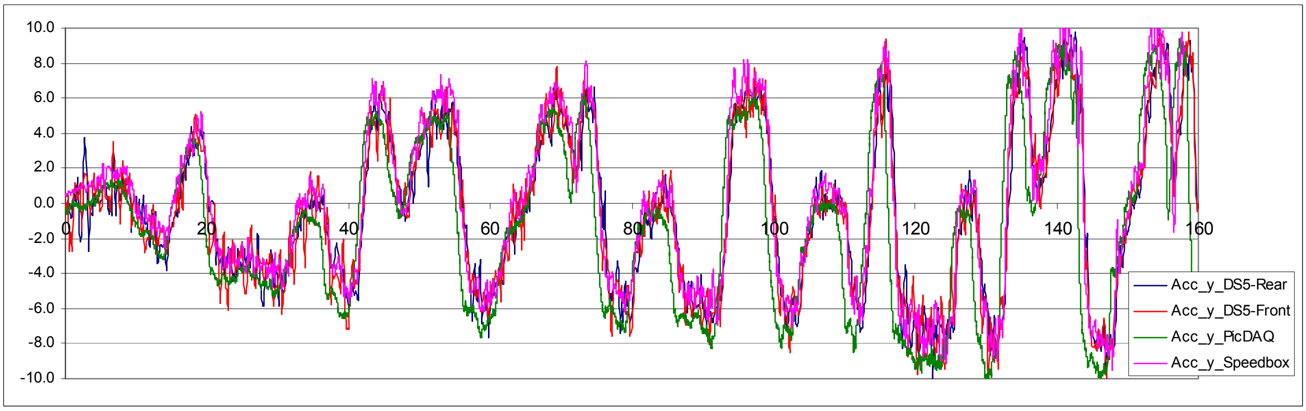

Fig. 7. Lateral accelerations measured with two GPS units, PicDAQ and the combined GPS/INS sensors (Speedbox)

Starting from the vehicle speed and the turning radius, the yaw rate can be calculated. Also the yaw rate can be estimated as the variation of the heading of the vehicle. In Fig. 8 is the diagram of the yaw rate calculated as *v/R*, where *v* is the speed of the vehicle and *R* is the turning radius. If the yaw rate is deducted from vehicle heading (Fig. 9), the radius of turn can be calculated, instead of using three succesive points. The method should be chosen depending by the goal of the study and the performances of the GPS receiver. The diagram shown in Fig. 8 uses filtered data, as the values resulted from calculation were too noisy.

Fig. 10 shows also the yaw rate, measured with inertial sensors (gyroscope), as raw data and filtered. The gyro measurements are affected not only by the measurement noise, but also by the sensor bias. Putting the diagrams obtained for the inertial sensor and for GPS receivers together, on the same graph (Fig. 11) is clearly visible a difference between the curves, which is incresing with the time. As a reference that can help in choosing the appropriate parameters for filters can be used the diagram in Fig. 12, based on data measured with Speedbox, which is quite close to the diagrams obtained for the two independent GPS receivers.

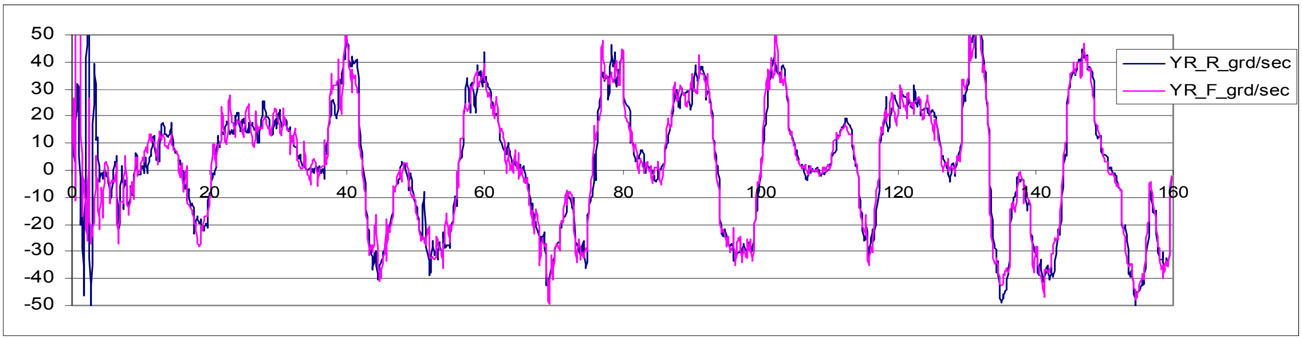

Fig. 8. Yaw rate calculated based on the speed and radius, for two independent GPS receivers

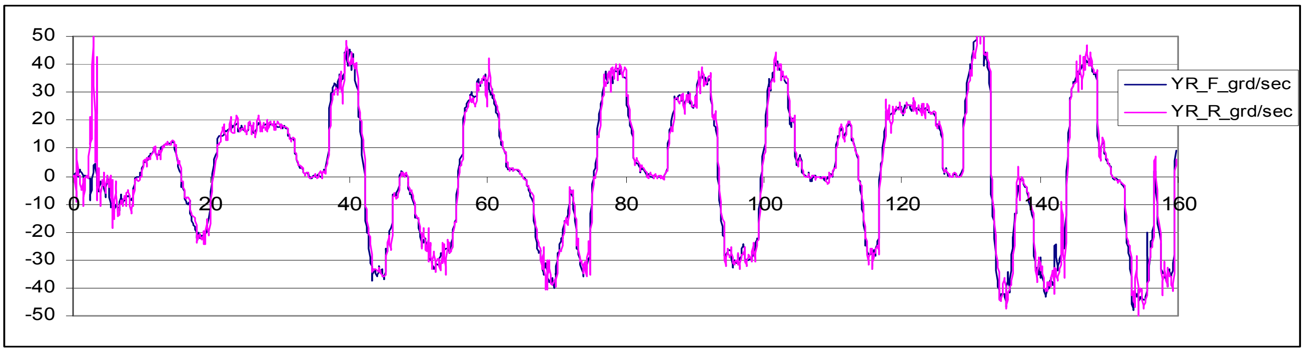

Fig. 9. Yaw rate calculated based on the heading, for two independent GPS receivers

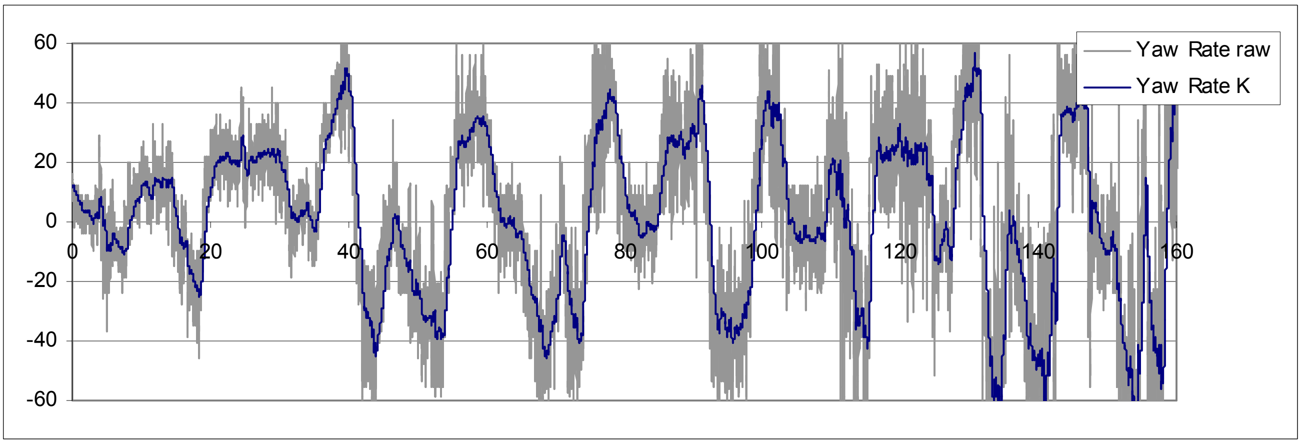

Fig. 10. Yaw rate measured with PicDAQ unit, as raw data and Kalman filtered

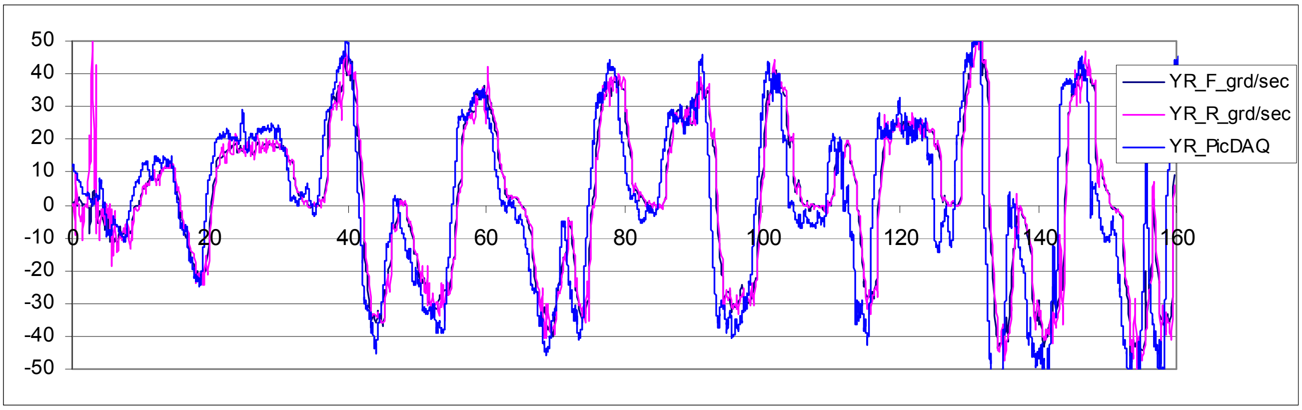

Fig. 11. Yaw rate calculated for GPS receivers and measured with inertial sensor (after filtration)

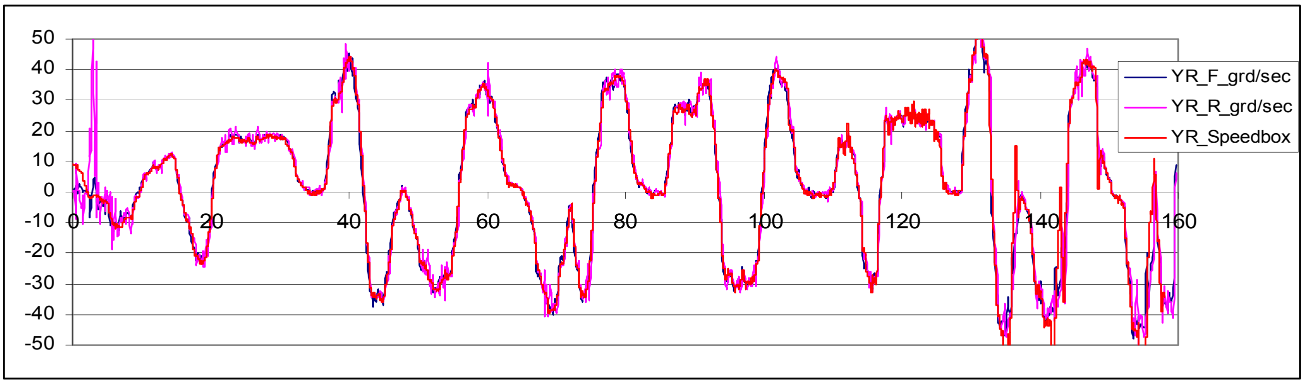

Fig. 12. Yaw rate measured with Speedbox and calculated for the independent GPS receivers

From equations (3) and (7), considering that the yaw rate is calculated based on the heading variation, it can be calculated the lateral acceleration as the product between speed (in m/sec) and yaw rate (radians/sec). The result is presented in the following diagram (Fig. 13).

It can be observed that the acceleration for the rear antenna has more variations than the acceleration for the front antenna (data used are not filtered).

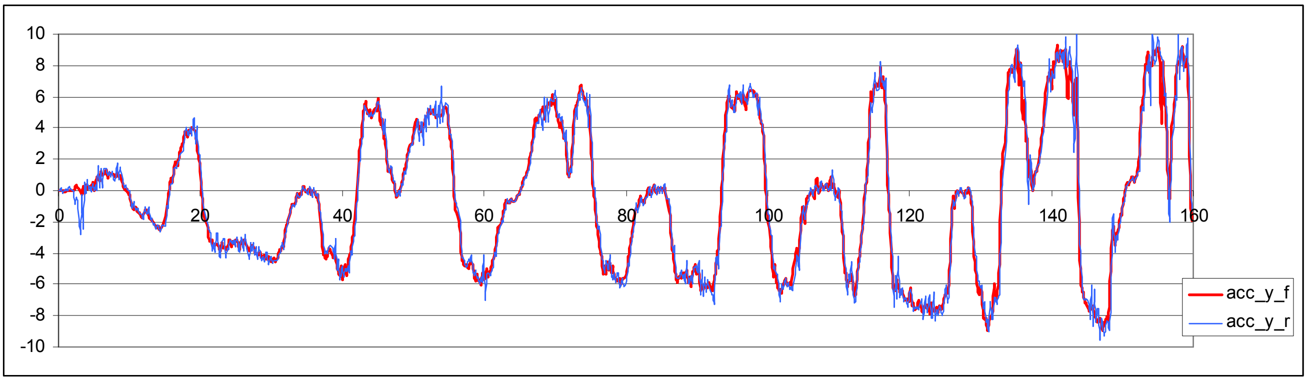

Fig. 13. Lateral acceleration for the two independent GPS receivers, based on speed and yaw rate

The sideslip angle can be defined as the difference between the vehicle heading and the direction of the velocity, for any point on the vehicle body. The vehicle heading is the same as the vehicle yaw angle. However, the GPS course is not necessarily the same as the vehicle heading. When using two GPS antennas in front and rear of the vehicle roof, there will be two headings measured by them, as shown in Fig. 14. The differences are visible only in sharp turns, when the lateral acceleration is also higher. If we consider the rear antenna as reference (like in case of Speedbox and other dual antenna systems [9]), the difference in the headings measured with two antennas can give the vehicle body yaw angle. However, both measured heading values are affected by the measurement noise. As the distance between antennas is known (and fixed), using a portion of the track with straight drive will give the possibility to reduce the effect of the measurement noise. This means a part of the record with constant heading, which can be identified on the diagram in Fig. 14.

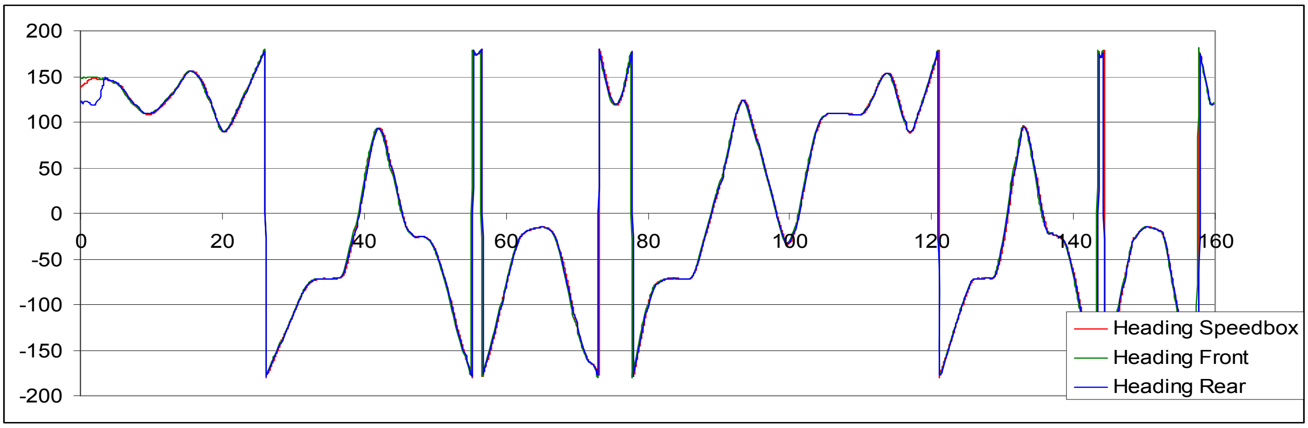

Fig. 14. GPS course measured with two independent receivers (DS-5) and Speedbox

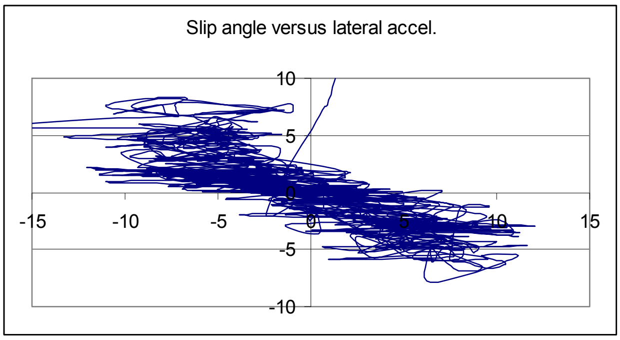

Fig. 15. Vehicle lateral slip versus lateral acceleration

So, knowing the speed and course for two points on the vehicle body, as well as the fixed distance between these points and using a straigth line driving on the track as reference, we can estimate the lateral slip of the vehicle. There is a direct dependance between the lateral slip and the lateral acceleration, which can be seen in Fig. 15. In normal driving condition (a normal driver in traffic) the slip angle will be less than 2 degrees.

Longitudinal acceleration is calculated using formula (8) and is also measured directly with the inertial sensor. The diagrams for the three acquisition systems are represented in Fig. 16. Data from DS-5 are calculated, those from PicDAQ are given by accelerometer and filtered (using the Kalman filter) and data from Speedbox are obtained both from speed variation and from inertial sensor.

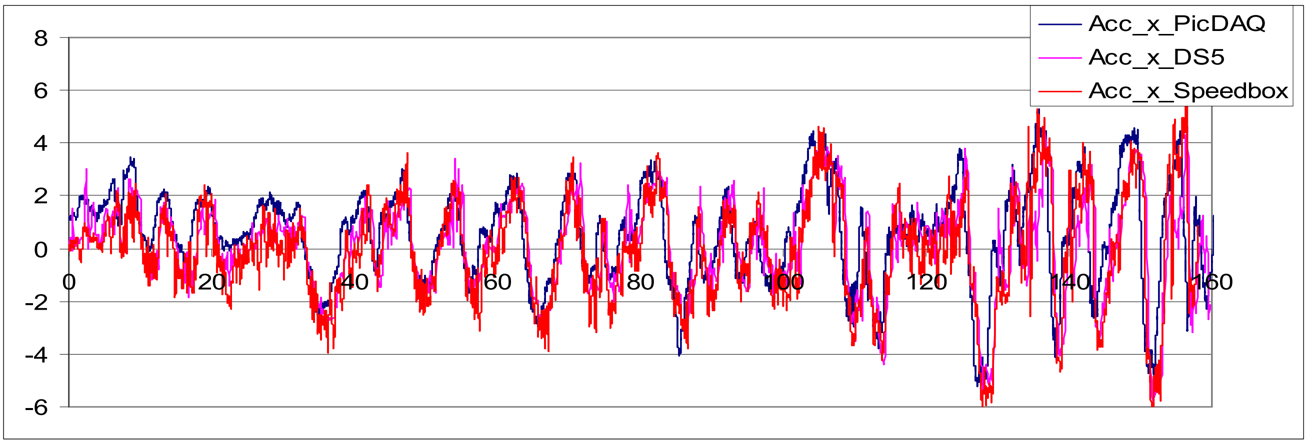

Fig. 16. Longitudinal acceleration

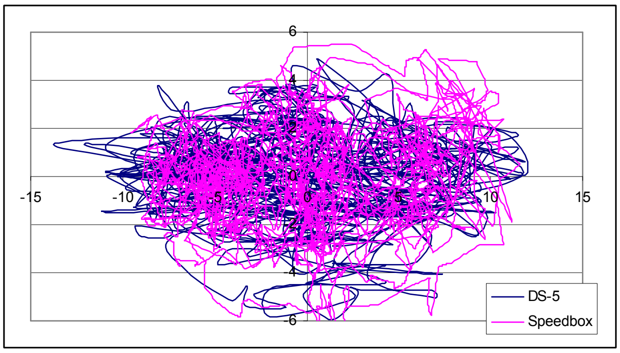

Fig. 17. G-G plot diagram

The lateral and longitudinal acceleration plotted together on the same diagram will give the G-G plot in Fig. 17, which is used in analysis of driver's performances.

Conclusion

The control systems (like for example the electronic stability control) installed on modern vehicles use information about the state of the vehicle. In order to obtain the necessary information, the cars are equipped with various sensors, measuring the steering wheel angle, wheel angular velocities, lateral acceleration, and the yaw rate. External measurement systems are used to validate the vehicle embedded systems, and also to identify new solution for improving the functionality of vehicle systems.

Data measured with IMU devices and GPS receivers lead to similar results, and all of them can be used to estimate the vehicle attitude. However the collected data are influenced by measurement noise and appropriate filtering needs to be used. A dual antenna GPS system combined with INS sensors will give the most accurate results in various conditions, but a system that uses two independent GPS receivers will be close, as long as the receiving conditions are very good and stable. Losing the signal for one of the two receivers will compromise the data and this should be compensated with INS devices. Also the INS devices features higher sampling rates than the GPS based systems.

The analysis conducted in this study revealed that all the data acquisition systems can be used for the study of vehicle's dynamic performances, but depending by the parameters tested some of the systems may be more appropriate than the others. When is measured the yaw, lateral acceleration and sideslip of the vehicle, the dual antenna GPS systems are a good choice, but they are not so appropriate for pitch and roll, when the accuracy of altitude measurement is not enough. Combining these systems with inertial sensors, all vehicle movement parameters can be estimated satisfactorily.

This study, and similare ones, are also premises for developing another original acquisition system, that will combine GPS and INS devices.

Acknowledgement

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