VEHICLE DINAMICS STUDY
BASED ON GPS DEVICES

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***Abstract**: The GPS technology is more and more widespread between common users, mainly for navigation applications, but to date the GPS devices performances become good enough to be used as tools in research activities. The price and easiness of use make this type of devices extremely interesting for the experimental study of any vehicle type dynamics. This paper shows some possibilities to process GPS data, allowing obtaining useful information about the vehicle dynamics behaviour. Also are presented and compared the data obtained from various GPS devices.*
The authors realised a computer program that run in AutoCAD environment, taking benefits from its graphical and list processing features. The data can be imported from different GPS devices using standard or proprietary file formats. Based on position and time information, it can be ascertained the speed, acceleration or slope and can be estimated the moving resistance forces and the power delivered by the engine. These results were represented as plots in different ways, for easy interpretation.

***Keywords**: vehicle dynamics, GPS, data acquisition and processing, CAD programming*

1. INTRODUCTION

In the last years, the GPS technology became common and popular. On the market are offered various applications, especially for navigation and for recording of the route travelled by different vehicles (aircraft, ships, cars) or pedestrians (on city or on mountain trails). Combining position information obtained from GPS with detailed digital maps, it can find the desired destinations and the optimum routes to follow.

The diminishment of electronic-devices price and the precision offered by the GPS, even for commercial applications, encourage the apparition of more and more new applications.

This paper presents possibilities to use GPS devices, designed and experinced by the authors to assess, by measuring and estimating, the dynamic behaviour of vehicles. Some results of the performed tests are also presented.

2. GPS DEVICES USED FOR THE STUDY

For the vehicle dynamics study were used four different GPS devices with tracking possibilities, presented in figure 1:

❖ Holux M-241, a GPS data logger, able to store a sample at every 5 seconds;

❖ Garmin GPSMap 60CSx [9], a handy and light-weight commercial device (1 sample per second recording rate, able to compute speed);

❖ Garmin GPS 18x-5Hz [10], a precise very small device (5 sample per second recording rate); connecting this to a notebook (figure 2) and realising an original software for real-time communication, data storing and primary processing (speed calculation, data filtering and trajectory graphical representation), the authors realised a valuable, affordable and easy to use GPS data logger;

❖ Racelogic VBox 100 [11], a professional device (with the recording rate up to 100 sample per second, able to compute speed and acceleration and graphical represent the gathered data in real-time).

Figure 1: The GPS devices used in measurements:
left – Holux M-241; middle left – Garmin GPSMap 60CSx;
middle right – GPS 18x-5Hz; right – Racelogic VBox (the blue case) and the previous two devices

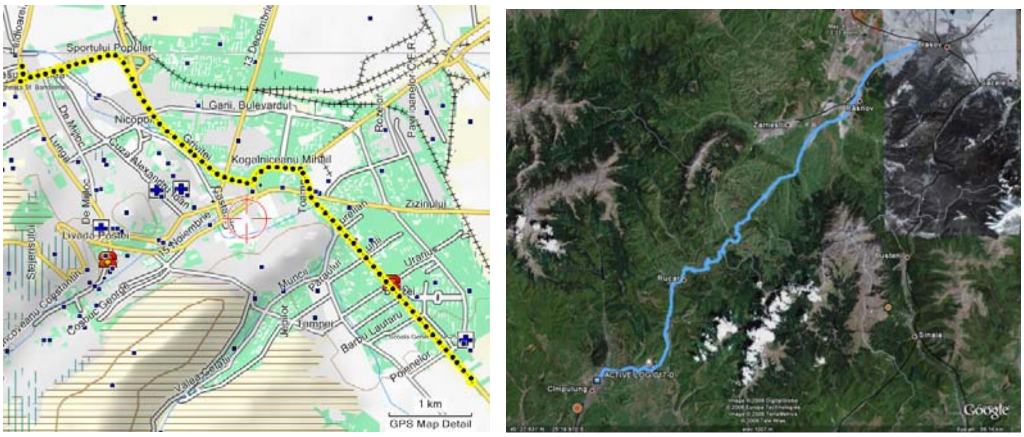


Figure 2: Tracks viewed in Garmin's MapSource software (left) and on Google Earth (right)

During the last three years, a lot of tests were made with these devices in order to verify theirs precision or for research purposes [6], [7].

Compared with other measuring devices used to study the vehicle kinematics, as the fifth wheel or Correvit optical device, the actual commercial GPS-systems present some important advantages: small packaging, reasonable prices, augmented performances, short time for vehicle instrumentation, easiness of use, simple connectivity with computers and ability to store large amount of data. Furthermore, any study of vehicle dynamics is based on reliable information about travelling time, acceleration, velocity and distance, which means exactly the processing results offered by common GPS receivers.

The recording of the altitude and geographical coordinates, also available, make GPS devices more attractive for the experimental study of vehicle dynamics, because the 3D profile of a track or a route can be easily obtained on a digital map [6], figure 2. Because each data sample is well identifiable in time, GPS information can be perfectly synchronized with test data provided by other measuring devices. The GPS tools can be used by day or by night, in on- and off-road applications, conditions in which other measuring instruments for vehicle kinematics can have difficulties to work.

Exterior mounting of small GPS antennae will not impede the vehicle's manoeuvrability or change its aerodynamics. If wonted, these can be even placed inside cabin, near the windshield. Also, simple data processing and plotting can be done in real-time, permitting very quick displaying of useful information.

3. BASE ALGORITM TO OBTAIN VEHICLE KINEMATICS FROM GPS DATA

The primary data, which one disposes after GPS tracking, are the time, longitude, latitude and altitude. The algorithm imagined and implemented by the authors starts with the transformation of that global positioning data in local x,y,z coordinates, according to the track mean position on the Earth [2]. As a result, the vehicle path is obtained as a series of three-dimensional points well related to the time, figure 3, left. Sorting these series of coordinates according to the time increase, a passing direction will be associated with the track, figure 5, left.

For the programming of the algorithm it was choose the Autodesk Autocad software for its capabilities in handling graphical objects and for the ability to process lists of its Autolisp programming language. This ensures to the researcher freedom and easiness in processing large amount of data.

All the information (time, geographical coordinates and CAD coordinates) is stored as a list of point properties. Another list will be made with line properties to store information referring to the intervals between consecutive points. New other information can be easily aided to these lists after new processing stages.

Based on the time and 3D coordinates of the points, for each pair of two neighbouring points, a time interval Δt and a distance Δs are calculated. Then, from these distances and time intervals, the mean vehicle velocities between points v_{med} are computed. This data is stored in the second list that contains the interval properties.

Each of the two ordered lists (with point properties and with interval properties) can be used according with the aim of data processing or visualization.

To estimate GPS-point velocities, the both lists can be used. One method can use an odd number (usually 3) of GPS-point time-space pairs (t_p,s_p), first to find by interpolation or interproximation a function s=f(t) and then to obtain the point velocity v as a derivative of this function, figure 3, right. The other method can use an even number (usually 2) of interval mean-velocities v_{med} to reach, by interpolation or interproximation, the point velocity v. Both methods were tested and the results are quite similar if ones compare with the velocities furnished by the GPS receivers. Based on that, the second method is normally preferred because is faster.

A similar approach was used to obtain the path slope. First a mean slope value α_{med} was calculated from the interval variations of the altitude and horizontal distances, then the GPS-point slop was reached by interpolation.

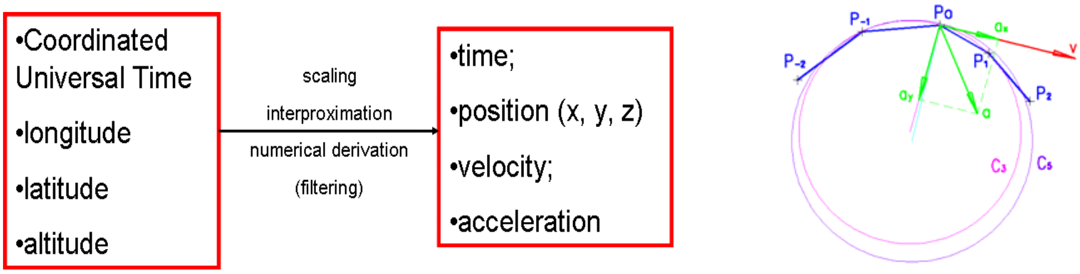


Figure 3: Schematic of GPS data processing (left)
and schematic of velocity and acceleration derivation from coordinates and time (right)

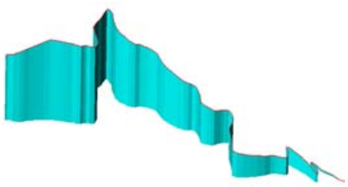


Figure 4: Three-dimensional representation of the trajectory (road's path and height)

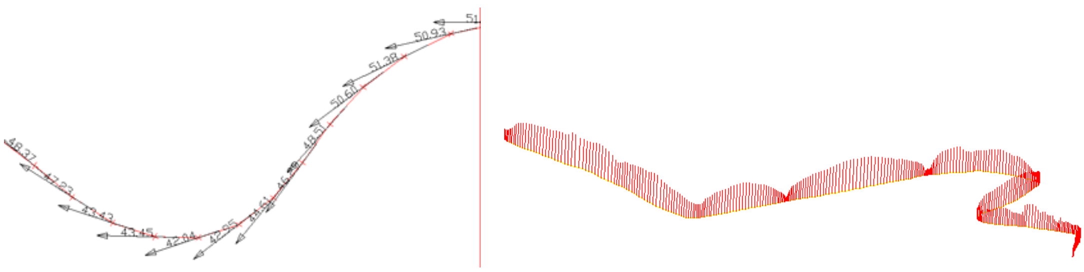


Figure 5: Modalities to represent speed evolutions on the trajectory
left – speed as vertical lines; right – speed as vectors with magnitude and orientation

Due to the graphical capabilities of the computer program, numerous types of visualisations can be used and automatically realised. As example, figure 4 shows a possibility to visualise the vehicle trajectory, permitting to observe the path as a 3D shape, with the possibility to mark local valleys and peaks or to graphically indicating certain levels of height. Figure 5 presents the plot of the vehicle velocity in the GPS-points. As can be seen, in the left side of the figure the vectorial representation indicates both the magnitude and the orientation of the velocity and in the right side the speed is represented as successive verticals to the path, indicating the vehicle stops.

To obtain the orientation (the heading angle, figure 5, left) it was necessary to realize first an approximation of the vehicle trajectory and then to represent the vector tangent to that, pointing in the travelling direction.

The simplest way to approximate a curved trajectory was to use a circle passing through three points: current, previous and next, figure 3, right. If the angle of the two line segments connecting the three vicinal points is too small, a straight-line trajectory was assumed (a curvature radius approaching infinity). For the other cases, the velocity vector orientation is perpendicular to the circle radius in the current point.

Of course, there are also other methods to approximate a trajectory when ones know its points. For example, the radius of curvature can be obtained using cubic spline interpolation or interproximation and then applying the second-order derivative function. The radius of curvature R was used also to calculate the lateral (centripetal) component of the vehicle acceleration:

$$a_y = v^2/R \qquad \text{(Eq. 1)}$$

The other component, the longitudinal (tangential) acceleration a_x obtains as the first-order derivative of the function $v_p=f(t)$ that estimate the magnitude of the vehicle speed.

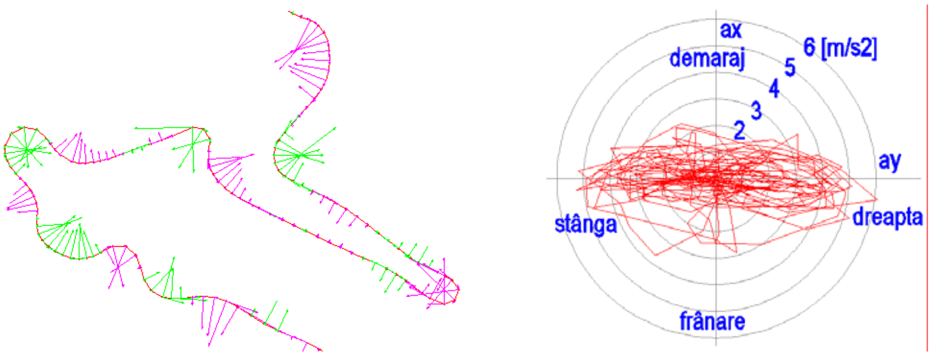


Figure 6: Acceleration's lateral and longitudinal components, represented on the track (left) or as radar plot or g-g plot (right), showing the handling ability of the driver-car par

Figure 6 shows the lateral and longitudinal components of vehicle acceleration. In the left side, the green and magenta vectors indicate left-hand, respectively right-hand turn. The vectors tangent to the trajectory mean braking, if are pointing rearwards (before turns), and gearing-up, if are pointing forward (after turns).

The total acceleration of the vehicle can now be calculated by a vectorial summation of the lateral and longitudinal components. The magnitude is:

$$a = (a_x^2 + a_y^2)^{0.5} \qquad \text{(Eq. 2)}$$

The magnitude and the orientation of the total acceleration with respect to the vehicle coordinate system can be plotted in a so called g-g plot (radar plot), as in figure 6, right. Such a polar representation gives us an idea about the vehicle-driver system's performances or about the mean stress and grip of the vehicle tires.

The open data-structure and the experience obtained by the authors facilitate the improvement and development of new procedures (used to manage large amounts of GPS or other-source data), as:

- a graphical user interface (GUI);
- new software procedures, which permit to select only part of data or to retrieve and further process geometric and kinematic information directly accessing already-existent graphical-objects, as plots, lines or points; for example, starting from an existent speed plot it is possibly to directly obtain a new filtered curve, the histogram and the mathematical derivative (acceleration) or integral (distance);
- different possibilities to filter the numerical data.

Also, numerous data-import and -export types are already implemented.

4. ASPECTS REGARDING THE MEASURING PRECISION OF GPS DEVICES

Since the functioning of the GPS relies on receiving high-frequency radio signals, the data precision or even the usability can be affected by obstacles interposing between the satellites and GPS receivers [8]. That means the GPS-based measuring techniques are not suitable in lab research or on routes passing tunnels, canyons or forests.

The main Causes of GPS-receiver errors are: receiver imprecision (clock, gain); multipath and reflection (up to 0.5 m); atmospheric effects (up to 10 m); reduced visibility (at least four visible satellites needed); selective availability (intentionally induced); human's wrong device operation or data interpretation. Also, the altitude error is bigger than the latitude or longitude error. Fortunately, for small distances (metres) and short time intervals (seconds), the position will be not affected too much, that means the relative position error between neighbouring points will be not to high.

The errors, introduced by the derivative functions needed to obtain speed and acceleration from position information, are relatively easy to control by numerical filtering procedures.

In time, the authors made numerous and systematic tests to verify if sensitivity, position accuracy and position repeatability of the available GPS devices are good enough to be used in researches [3], [4], [5]. To put in evidence different kind of errors, different test types were performed:

- recording simultaneously the same track with more GPS receivers of the same or different types;

- recording the same track with one receiver at different moments of time (in the same day or in different days);
- simultaneously recording of the same track with one GPS receiver and other measuring tools (for example comparing the speed supplied by a GPSmap system with the same information computed by the ABS controller and obtained by logging on the vehicle CAN, via an OBD II software);
- measurements kipping immobile the GPS receiver for a longer period of time;

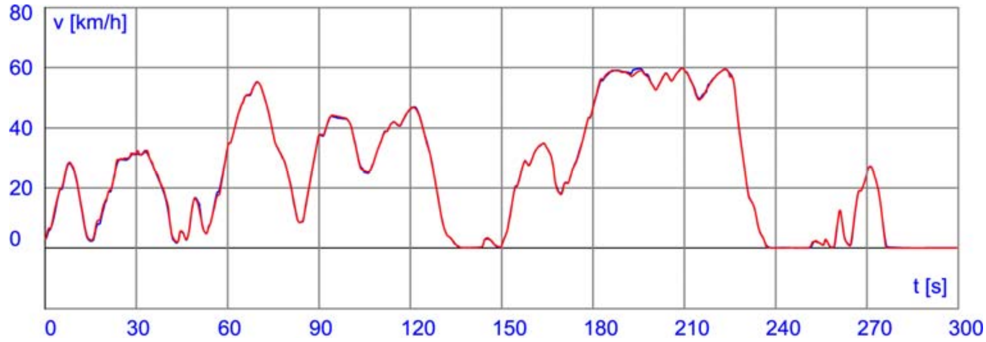


Figure 7: Plots of simultaneous speed records obtained with two similar GPS devices (Garmin GPS 18x-5Hz) placed very close one to other

Such test example can be seen in the figure 7: the speed information obtained from the primary global-position data, using the presented algorithm, without filtering, is almost identical for two similar GPS devices that were placed very close one to other.

The conclusion was that, in the majority of studies, the modern global positioning systems offer good precision and are suitable for researches implying vehicle kinematics and dynamics.

5. ASPECTS REGARDING VEHICLE DYNAMICS OBTAINED FROM GPS DATA

The experimental data regarding the vehicle kinematics can be used as it is. Often simple representations versus time (figure 8 and figure 9, up-middle) or versus travelled distance (figure 9, down-middle) are sufficient. For example, figure 8 shows the maximal acceleration and braking performances recorded in straight-line motion. In the left side ones can see evolutions of speed and acceleration during a vehicle take-off immediately followed by a hard braking. The data was recorded and plotted with the VBox system. Due to the logging rate of 20 samples per second, rapid phenomenon can be observed clearly, as gear changes, clutch engaging shocks or ABS cycles.

In the right side of the figure 8 the VBox data of the left side was imported in Autocad and plotted with the described program in order to compare four records: two obtained with the same car in successive tests and the others obtained with other two cars. One can observe that the first vehicle starts from rest almost identically and its pulling performances are superior to the other cars.

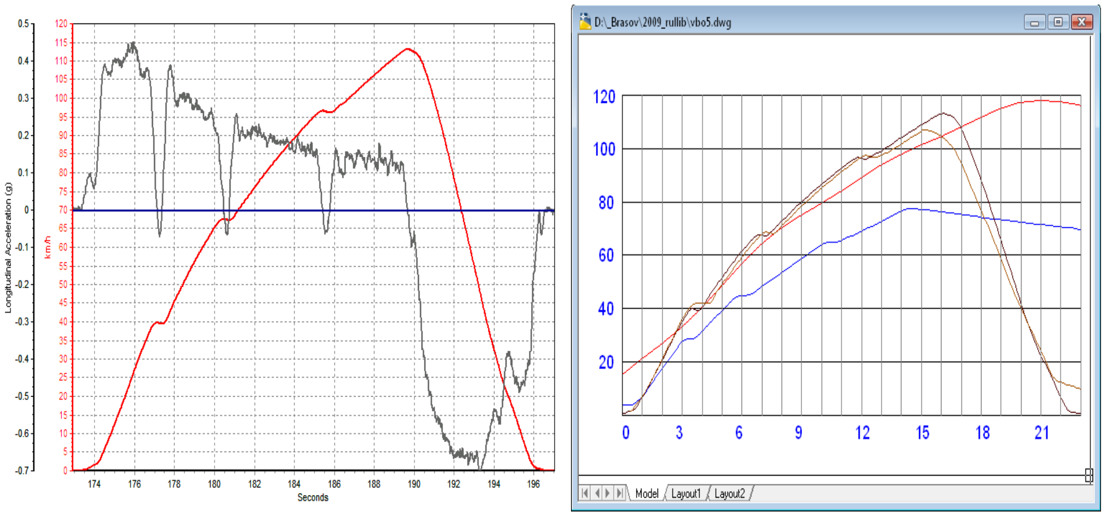


Figure 8: Example records of starting – braking tests
left – singular speed- and acceleration-plot; right – multiple speed plots of three cars

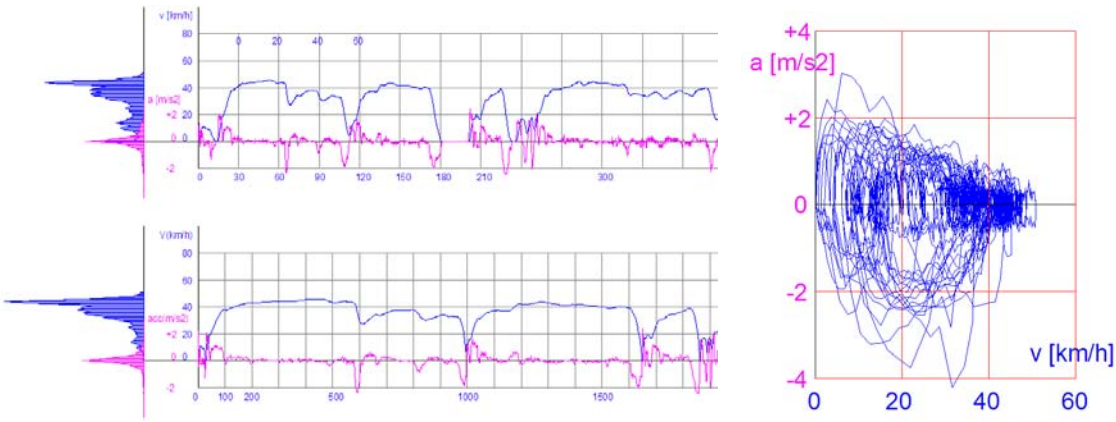


Figure 9: Speed and acceleration representations (urban conditions): left – histograms; middle – fragments from plots vs. time (up) and vs. distance (down); right – city driving cycles

Figure 9 shows a way to take the time- or distance-related information of vehicle speed and acceleration (presented as a fragment in the middle area of the figure) and to represent it (the right side) or statistically process (the left side) so that to obtain a good perception of the vehicle dynamic behaviour in given conditions. Such graphical representations as in figures 9 and 10, left, give the possibility to know what speed or acceleration regimes are more probable (are found more often) during driving.

First dynamic evolutions that may interest are the vehicle's total resistance force and his components: the rolling resistance, the grade (slope) resistance and the aerodynamic drag. In this case, the measurements will include the determination of the vehicle total mass and its repartition on each wheel, the vehicle frontal area (for example, using a scaled photograph) and an estimation of the rolling drag coefficient measured on a roller dynamometer or obtained by coast-down (free-rolling) tests [1]. Other operations, as the measurement and regulation of the tire inflation pressures or the readings of atmospheric temperature and pressure, may be very useful for results comparisons or interpretations.

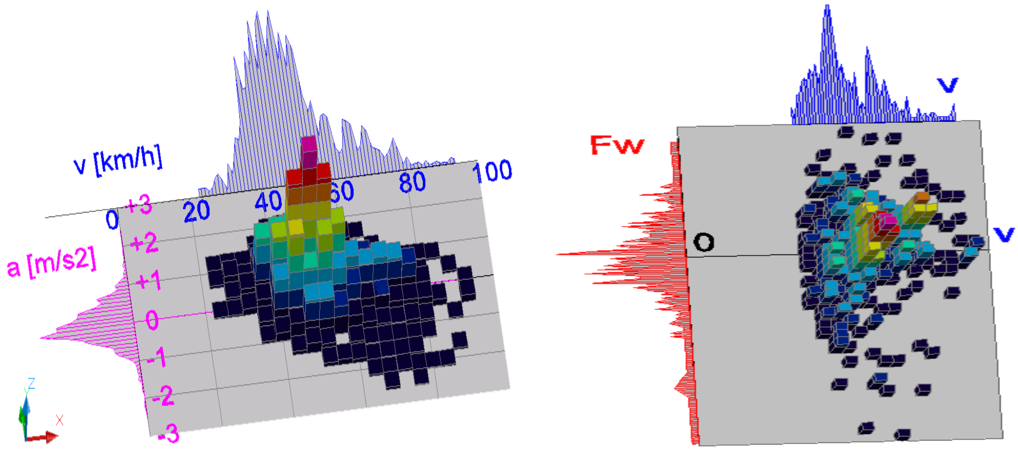
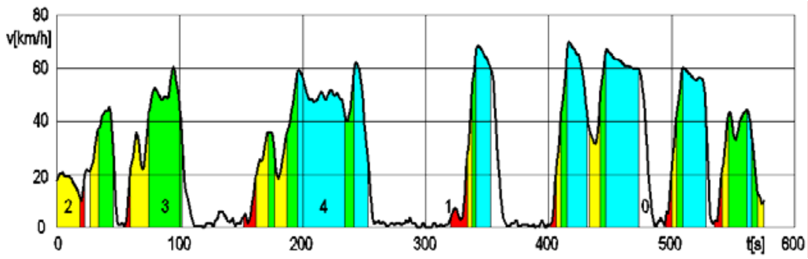


Figure 10: Mono- and bi-parametric probability density functions for mountain route left – speed and acceleration; right – speed and traction/braking force



Gear	Time [%]	Dist [%]	Vm [km/h]
0	36.3	8.7	6.6
1	8.5	2.7	8.9
2	15.8	15.1	26.4
3	17.4	28.4	45.3
4	22.0	45.1	56.6
Total	100	100	27.7

Figure 11: Car-speed evolution with gear indication in city route (time plot and statistics)

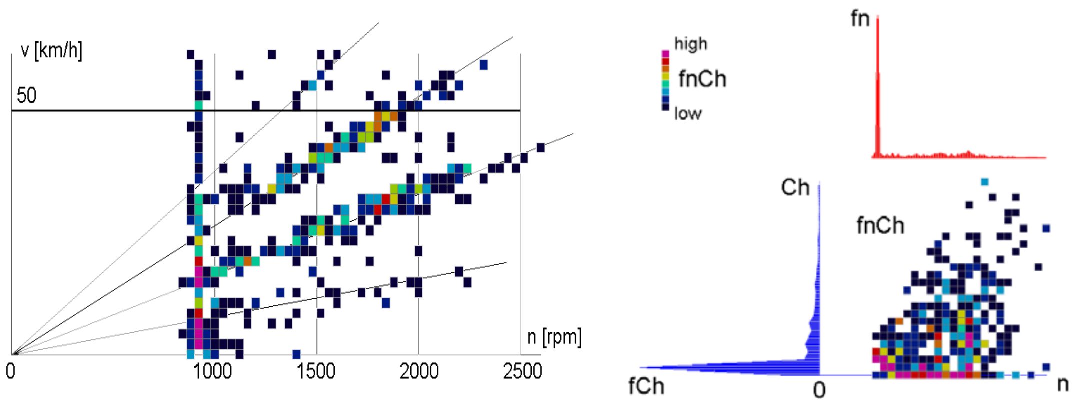


Figure 12: Experimental mono- and bi-parametric probability density functions for city route left – engine speed and road speed; right – engine speed and hourly fuel consumption

Starting from experimental kinematics and using such supplementary measurements or even assuming some vehicle parameters, it is possible to estimate very important dynamic values as motion resistance forces, traction/braking-force or -power [3]. The right-side of the figure 10 presents statistical information regarding the uni- and bi-parametric probability to drive a car on an un-congested mountain road with certain speed and force applied to the wheel (traction or braking force). This histogram is related to the travelled distance, while the histogram from the left side is related to the travelled time.

The experiments' importance can be further increased if it is possible to pass from the vehicle kinematics (distance, speed, acceleration) to the dynamics (forces, torques). Thereby, to obtain valuable results about vehicle dynamics, supplementary experimental determinations must be performed immediately before or after the GPS-data recording. The number of these laboratory measurements depends of study's aim and complexity.

The combination of the acquired kinematic data with other information types can be realised easily with the presented computer program due to the open structure of data, to the possibility to extract sub-sets of data and to the graphic capabilities. Figures 11 and 12 are examples of how data obtained by GPS and by other sources (marks manually introduced, on-board computer or instrumented sensors) can be mixed to obtain extremely helpful results.

Figure 11 shows a processed plot of the vehicle speed in urban driving. Manual marks (permitted by the receiver Garmin GPSMap 60CSx, memorising the time and the coordinates) were added to indicate the gear changes. These permitted to obtain the statistics of the gear use, as is presented in the right-side of the figure. Assuming zero wheel slip and knowing the transmission ratios and the tyres' dimensions, the engine speed can be computed in any moment. Also, if the driving force and the efficiency of the drivetrain are estimated, the approximation of the engine torque is also possible.

OBD software permits today to access the vehicle communication network. The data furnished by the on-board sensors, through the vehicle computer and CAN interface, can be easily synchronised with the GPS data.

Figure 12, left, presents a histogram obtained by the combination of the engine speed read from CAN and the vehicle speed provided by GPS on city traffic. The engine idling and the engaged gear can be recognised, even powertrain vibrations or clutch-slippage or -disengagement alter the straight-line shape. In the same manner, the right side of the figure presents the graphics of mono- and bi-parametric probability density functions for the engine's speed and hourly fuel consumption, obtained from the on-board computer data.

6. CONCLUSIONS

Professional GPS systems ensure global positioning records of high accuracy, allowing using them in precise studies aiming the vehicle behaviour on the path. The short time needed for instrumentation, the ease of use, the simplicity of connection to portable computers and the universal time information are key qualities that make them preferable in vehicle dynamics studies. To these elements one can add the rapid improvement of performance-price ratio, which currently allows utilising common-use commercial-receivers to carry out extensive and accurate researches.

Although the positioning accuracy is increasing continuously, the errors remain an important problem, quite difficult to control, especially in environments that detract or partly diminish the satellites visibility.

However, a proper use in correlation with quality processing-algorithms permit to the GPS systems to provide a precision of speed and acceleration measurements at least as good as other measuring systems used in experimental research. But comparing with other systems, the GPS devices have the advantage of very precise time measurement, perfect synchronization with other devices and motion trajectory recording.

The GPS-based method presented here proves to be accurate enough for vehicle kinematics measurements, in different on-road and off-road condition, including urban environment. With some precautions and less accuracy, it is also applicable to determine the road profile (altitude and slope).

Performing supplementary laboratory-measurements or adopting approximate values for different vehicle parameters, the method can be extended to assess the vehicle's dynamic behaviour, or more, to calculate in-traffic fuel consumption, for estimating the level of chemical and noise pollution, or even to conduct fatigue calculations (variable stress) for different vehicle parts.

Bi-univocal connections between the points on the diagrams and the geographical data permit the complete identification of each GPS-point and, as consequence, a better interpretation.

The method can be easily adapted to measure the kinematics and to estimate the dynamics of other vehicle types, as boats, ships, aircrafts or trains, as the better satellite-visibility is a premise for an even better measurement precision. As the authors intend to experiment further, combining the data of two or more GPS devices, used simultaneously, it is also possible to derive the vehicle rotation movements: roll, pitch and yaw. For large vessels, for example, this information may be used to estimate the dynamical stresses applied to the vessel hull or propulsion and steering systems.

Obtained by the processing of large amounts of data, such event- or statistical-information can be extremely useful for different types of studies.

As this work tried to prove, it is expected that the number of future uses of GPS systems to grow in the near future in a very large extent.

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