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VEHICLE DYNAMIC BEHAVIOUR ANALISYS BASED ON GPS DATA

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Abstract: *GPS technology has a wide spreading for the large public. Now, it has enough advantages to be considered as a useful tool in the research activity. The price and the easiness of use make that type of devices very interesting for the experimental study of terrestrial vehicle dynamics. The paper presents some GPS data processing possibilities figured out by the authors. Valuable information regarding the vehicle kinematic and dynamic behaviour can be obtained. The authors realised a computer program that run over the AutoCAD platform, valorising its geometrical and list processing capabilities. The data can be imported from different GPS devices using standardised or proprietary data formats. The information can be split, trimmed or merged for adjusting the track records to the researcher specific needs. Also, the results can be exported in some large accepted formats, to be used in spreadsheet applications as Excel or in mapping software as standard GPX file format. Starting from time and three-dimensional position data, the vehicle velocity, acceleration, road slope, movement resistance force or powers and engine load can be derived. This kind of results can be plotted in diagrams for easier interpretation in domains as traffic flow statistics, fuel consumption, energy recuperation and vehicle load estimation.*

Keywords: *vehicle dynamics, GPS, data acquisition, software tool, CAD programming.*

1. INTRODUCTION

The GPS technology becomes more commonplace on the commercial market. Different applications are already offered, mainly used to guide and track vehicles (airplanes, boats, cars, buses, trucks) or pedestrians (walking on cities or climbing mountains). Combining GPS position information with detailed maps, on-board navigation systems help drivers to find a destination or to choose optimal routes.

Beside the existent applications, even more new others start emerging. This tendency is favored by the down scaling of the electronic devices, price decrease and performance augmentation of GPS receivers.

This work presents some modalities, imagined by the authors, to use GPS data for the vehicle dynamics evaluation (measurement or estimation). Also, several results, obtained in road tests, are presented. These are based only on GPS data or are obtained as a combination of experimental data provided by different sources.

2. NATURE OF GPS INFORMATION

A user's GPS device receives high-frequency radio signals transmitted by a network of convenient placed satellite on the Earth ionosphere.

When the data furnished by at least four satellites is available, the GPS receiver is able to associate the Coordinated Universal Time with the computed longitude, latitude and altitude information. The process of storing these time series of global coordinates is called "tracking".

Depending on the GPS receiver performances, the global coordinate samples can be reached at different rates (up to 50 per second). Based on the current and anterior (one or more) samples, containing time and three-dimensional coordinate information, the GPS receiver is commonly able to compute derived information as traveling distance and velocity.

These data flows can be transmitted in real-time to a computer or can be recorded in the device's available memory, for later processing.

3. POSSIBILITIES TO USE GPS DEVICES FOR VEHICLE DYNAMICS STUDY

Any study of vehicle dynamics bases on reliable information about traveling time, acceleration, velocity and distance, which means exactly the processing results offered by common GPS receivers. The records of the altitude and geographical coordinates, also available, make GPS devices more attractive as testing tools for vehicle dynamic behavior study, because the 3D profile of a track or a route on a digital map can be easily obtained.

Fig. 1. Concrete road track used for tests

Fig. 2. Test vehicle used for road experiments

As was already mentioned, the actual commercial systems have small packaging, reasonable prices, augmented performances. Furthermore, there are other advantages, as short time for vehicle instrumentation, device using easiness and simple connectivity with computers.

Because each data sample is well identifiable in time, GPS information can be perfectly synchronized with test data provided by other measuring devices.

Since the functioning of the GPS devices 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. That means the GPS-based measuring techniques are not suitable in lab research or on routes passing tunnels, canyons or forests.

In return, the GPS tools can be used by day or by night, in on- and off-road applications, conditions in which other vehicle kinematics measuring instruments can have difficulties to work. Also, the data processing can be done in real-time, permitting very quick displaying of useful information, or as post-recording, allowing the storing of large amount of data.

Figures 1 and 2 show one testing track and one car used in experiments. As can be seen from figure 2, no exterior mounting impedes the vehicle's maneuverability or change its aerodynamics, because the small GPS antenna is placed inside cabin, near the windshield.

4. ASPECTS REGARDING THE QUALITY OF GPS INFORMATION

The most used measurement properties to characterize a GPS receiver performance are:

- sensitivity, that defines the lowest satellite power level at which a receiver is still able to track and achieve a position fix on satellites overhead;
- time to first fix (TTFF), that is the time that it takes for the receiver, after its start, to return its actual location; most modern receivers normally need less than 60 s; the sensitivity and time to first fix significantly affect the receiver's usability;
- position accuracy, that represents the GPS error for only one position indication; today,

receivers are able to achieve better than 5 meters of maximum error, with typical errors as low as 1 to 2 meters;

- position repeatability, that represents the GPS error appearing between repeated position indications (at different time moments).

The main sources of error for GPS measurement are:

- the quality of the receiving device, affected especially by the precision of its internal clock;
- atmospheric effects, that change the signal speed with respect to the speed of light; without accurate ionosphere information, these can induce about 10 meters of error;
- reduced visibility, that can decrease significantly the power of the received GPS signal at ground level; materials such as plastic can degrade the signal;
- multipath errors, produced by reflected signals from surfaces near the receiver, that can either interfere with or be mistaken for the signal that follows the straight line path from the satellite; multipath influences is difficult to detect and sometime hard to avoid; these usually reduce the results accuracy with about 0.5 m;
- selective availability, that is an intentionally induced and controlled from the monitoring stations on the ground;
- human errors, produced by wrong device operation or data interpretation.

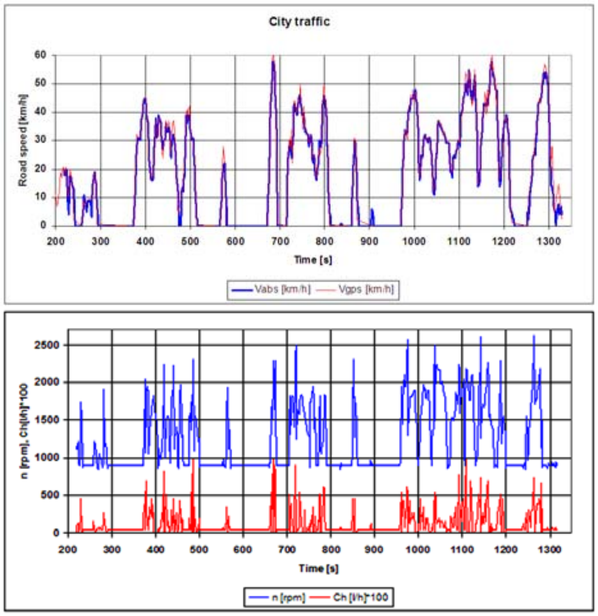

Fig. 3. Plots presenting city-traffic vehicle information obtained by combining time records from two data sources (GPS and vehicle CAN)

During experiments, three types of GPS receivers, all able to record tracks, were used:

- Racelogic VBox, a professional device, able to store or process in real-time signals received from two antennas (20 samples per second);
- Garmin GPSmap 60CSx, a device able to record tracks (more that 10000 samples at a maximal rate of 1 sample per second or 1 sample at 10 meters traveled); it can also memorize waypoints, at button press;
- HOLUX M-241, a GPS data logger, able to store a sample at every 5 seconds.

The data, recorded in the internal memory of each device, was exported to a PC using a USB connection. The VBox system can also display in real-time the selected signals and the GPSmap system can show the instant position and the recorded track on the map (figure 4).

To put in evidence different kind of errors, four test types were performed:

- measurements kipping immobile the GPS receiver for a longer period of time (more minutes);
- 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.

The upper plot in figure 3 shows the temporal evolution of a car velocity (from figure 2), in city traffic. The red curve presents the results furnished by the GPSmap system, while the blue one presents the data existent on the vehicle CAN and logged, via an OBD II software, on a laptop.

As can be seen, the superposition of the two data series is quite good, that means the both acquisition systems are reliable. It must be mentioned that the GPS velocity signal wasn’t filtered at all, that explains the higher pick values of the red curve. Also, after 1300 s, the two signals continue to be perfectly synchronized.

The lower plot presents the instantaneous engine speed [rpm] (the blue curve) and fuel consumption [l/h] multiplied by 100.

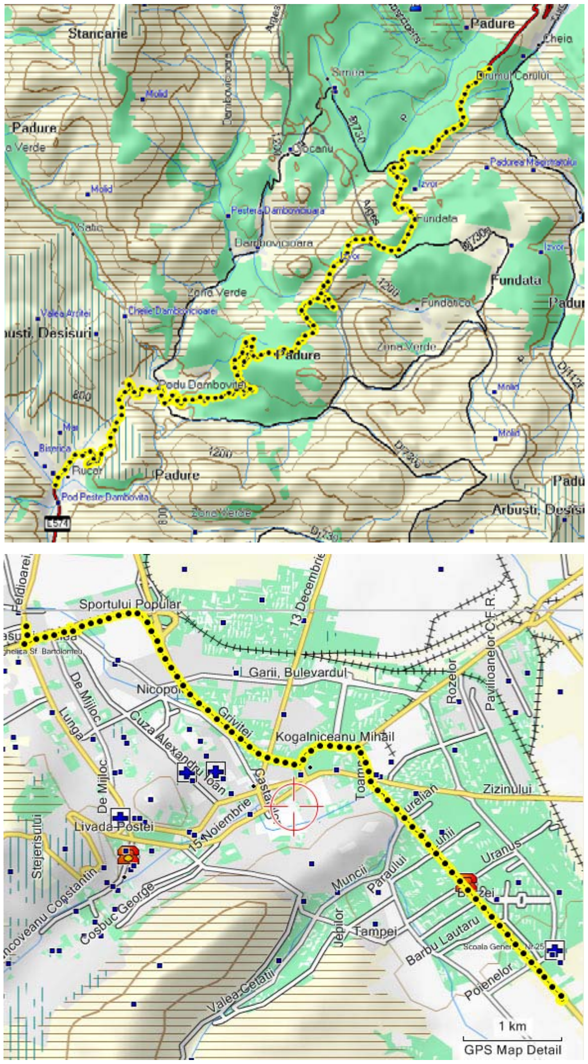

Fig. 4. Tracks viewed in MapSource (MapSource is a mapping software distributed by Garmin)
upper side – outside city; lower side – inside city

The plots in figure 3 show that test data obtained with common GPS systems are sufficiently accurate to be used in research activities, can be easily combined with data provided by other measuring devices and can increase the overall value of the investigation.

5. VEHICLE KINEMATICS ASSUMPTIONS AND ALGORITHM

The primary data, which one disposes after GPS tracking, are the time, longitude, latitude and altitude.

According to the track mean position on the Earth, the data about longitude, latitude and altitude are transformed in local *x,y,z* coordinates, permitting the visualization as a three-dimensional path. Sorting these series of coordinates according to the time increase, a passing direction will be associated with the track.

This information (time, geographical coordinates and CAD coordinates) is stored as a list of point properties.

Based on the time and 3D coordinates of the points, for each pair of two neighboring 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 as a new list containing 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 representation.

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. 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, between them and also with the velocities furnished by the GPS receivers. Based on that, the second method was 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 5 presents the plot of the vehicle velocity in the GPS-points. As can be seen, the used vectorial representation indicates both the magnitude and the orientation of the velocity.

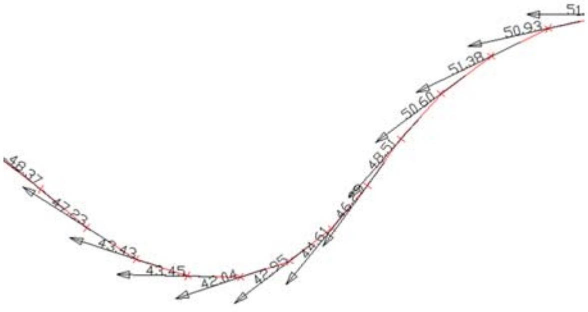

Fig. 5. Vehicle speed represented in the GPS-points

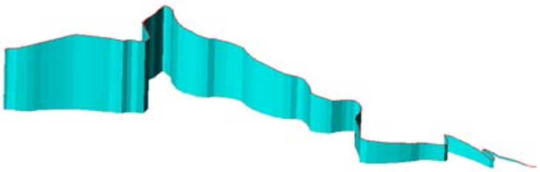

Fig. 6. Three-dimensional representation of a trajectory, evidencing the path height and slope

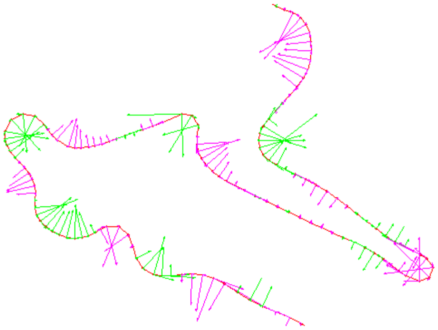

Fig. 7. Vehicle acceleration lateral and longitudinal components, represented on a track

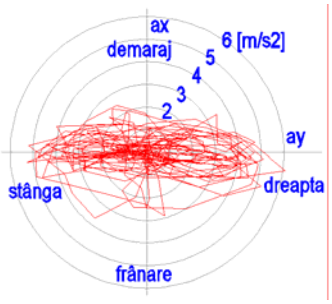

Fig. 8. Vehicle g-g plot obtained by traveling an uncongested mountain road

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

The simplest way to approximate a curved trajectory was to use a circle passing through three points: current, previous and next. 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 points of it are known. For example, using cubic spline interpolation or interproximation and then applying the second-order derivative function to obtain the radius of curvature. 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 velocity.

Figure 7 shows the lateral and longitudinal components of vehicle acceleration. 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, as in figure 8. Such a polar representation gives us an idea about the vehicle-driver system's performances or about the mean stress of the vehicle tires.

6. VEHICLE DINAMICS ASSUMPTIONS AND ALGORITHM

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 the aim of the study.

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.

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.

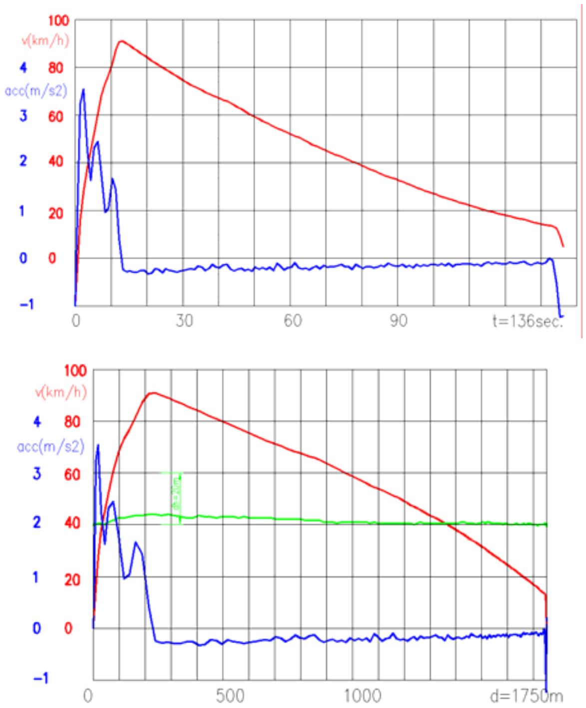

Fig. 9. Test drive consisting of pulling away from rest up to 90 km/h fallowed by coast-down

Good estimations of the rolling and aerodynamic drag coefficients as functions of vehicle velocity [1] can be obtained by processing coast-down records: vehicle moving by its inertia, with the engine disengaged, on a straight-line horizontal track.

The diagrams of figure 9 shows the evolutions of velocity and acceleration, versus time and distance, recorded on the track presented in figure 1. Statistically processing this deceleration data, for example by regression, an estimation function c=f(v) can be obtained for the resistance coefficient of the vehicle movement on horizontal road. This force represents the summing up of the rolling, aerodynamic and unloaded driveline resistances. Assuming cos$\alpha \cong 1$, it can be computed by multiplying the coefficient c with the vehicle's weight:

$$R_h = c\ W \qquad \text{(Eq. 3)}$$

Since the grade resistance:

$$R_g = W \sin\alpha \qquad \text{(Eq. 4)}$$

computes easily, the vehicle total resistance force R_{tot} achieves adding equation 3 and 4.

Adopting a value δ for the coefficient of driveline rotaries ($\delta \cong 1.03 \ldots 1.04$ for upper gears) and using the known longitudinal acceleration a_x, it is now possible to estimate the vehicle's force at the drive wheels:

$$F_w = R_h + R_g + \delta\ W\ a_x \qquad \text{(Eq. 5)}$$

Neglecting the drive-wheels slip, the power at the drive wheels P_w computes as:

$$P_w = v\ F_w \qquad \text{(Eq. 6)}$$

Continuing with the assumptions and adopting a value for the driveline efficiency η it is possible to estimate the effective power of the engine

$$P_e = P_w / \eta \qquad \text{(Eq. 7)}$$

Finally, knowing the overall transmission ratio i and the dynamic radius of the wheel r_d, obtain the engine speed:

$$\omega_e = i\ v / r_d \qquad \text{(Eq. 8)}$$

and the engine torque

$$M_e = P_e / \omega_e \qquad \text{(Eq. 9)}$$

Figure 11 shows the temporal evolutions of velocity, longitudinal acceleration, total resistance force, force at the drive wheels and power at the drive wheels, all estimated on the base of some minimal measurement and records with GPS data. The altitude of the traveled mountain road is also presented in figure 10.

If other devices are used in combination with GPS receivers, some or maybe all of the estimated values can be replaced by measured ones.

4. DATA PROCESSING AND RESULTS VISUALIZATION

To process the GPS-based measuring data, a computer program was written in Visual Lisp language to be used on the Autocad software platform [2].

This CAD software was preferred mainly for its ability to process vectorial graphic objects and reconfigurable data lists (automatically processing), but also for the easiness to adjust, modify or eliminate graphical features (on-demand processing).

The program permits a large diversity of graphical representation, ensures easy to manage new types of computations and flexible interconnection with other software or data formats.

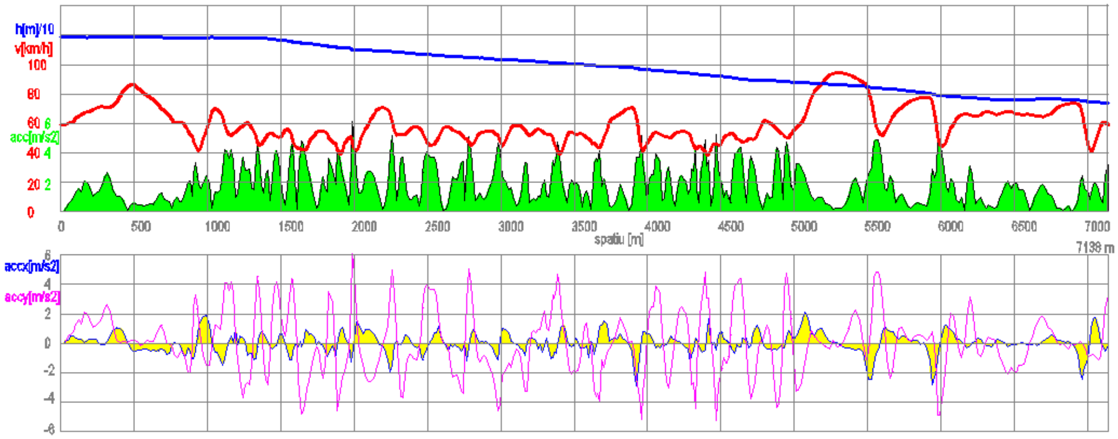

Fig. 10. Graphic presentation of vehicle kinematics characteristic parameters on uncongested mountain road
upper side: total acceleration, velocity and altitude;
lower side: longitudinal and lateral acceleration

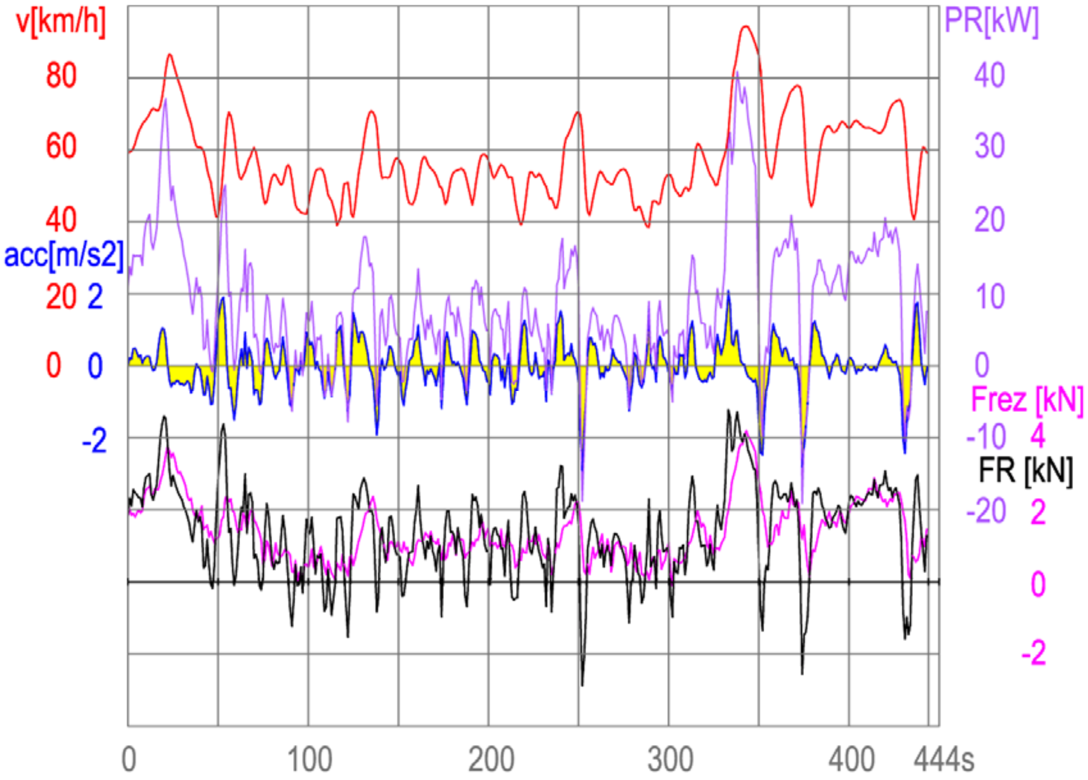

Fig. 11. Complex diagram presenting vehicle dynamics characteristic parameter on uncongested mountain road
upper side: velocity, longitudinal acceleration and power at the drive wheels
lower side: total resistance force and force at the drive wheels;

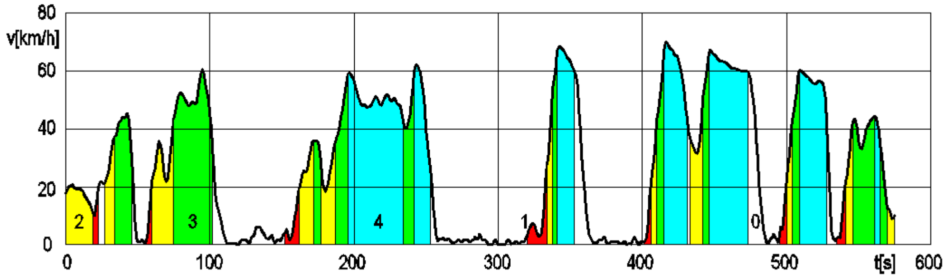

Fig. 12. Time diagram of speed and used gear on a congested urban route

Averaging functions for points (for ex. when the vehicle is stationary) or for tracks (for ex. when a route was recorded many times) are already implemented. Also, statistical functions (as min, max, mean) are present and was used inclusively for large records (more than 10000 GPS-points, 3 hours and 200 km travel).

New kind of information can be rapidly added. For example, using waypoints marked on the GPS device, it is also possible to add extra information that indicates gear shifts or other important events. In this case, a second person is required beside the driver, to mark the event's points during the travel.

The shifting points may be added on the diagram and then it is possible to synchronize theirs time and position with the recorded track. Figure 12 present such results for city traffic. The portions of the plot that correspond to certain gears can be shown with different colors. Hence, an interesting statistic was reached about the gears' usage:

neutral: 209 s (36.3%); 383.3m.
first gear: 49 s (8.5%); 121.4m.
second gear: 91 s (15.8%); 667.0m.
third gear: 100 s (17.4%); 1257.2m.
fourth gear: 127 s (22.0%); 1996.8m.
Total: 9 min 36 s; 4425.9m.

5. OUTCOMES

The program developed for analyzing data recorded by the GPS devices is in the development phase, and more features may be added in time. Designing a research tool, the authors focused on program functionality, leaving the interface development for the next stages. Beside the implemented function for data import-export, a larger interconnection with other acquisition systems and processing software is intended.

6. CONCLUSION

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

Performing extra laboratory measurements or some assumption, the method can be extended for the vehicle's dynamic behavior analyze.

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.

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