Precise Road Geometry for Integrated Transport Safety Systems

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Abstract

A safer mobility is a key concern for the strategy of the European governments and automotive industries. At the moment, a new generation of Intelligent Integrated Transport Safety Systems (IITSS) offers a promising potential to address this issue. Such co-operative systems will enable safety-concerning information to be exchanged between the vehicles or between the vehicles and the infrastructure. IITSS mainly involves sensors for detection and interpretation of the driving environment. One of the most significant related methods is the so-called Lane Departure Warning (LDW) since the unintended cross of the lane boundary is one of the largest cause of highway fatalities.

Implementation of LDW requires an accurate survey of the lane layout is necessary. The Geodetic Engineering Laboratory of the Swiss Federal Institute of Technology in Lausanne has designed a mobile mapping system *(Photobus)* that provides fast and accurate acquisition of the road geometry. Recent surveys carried out by *Photobus* in Switzerland provide good basis in establishing the optimal relation between the required point sampling and the model of the road geometry.

This paper focuses on methods for an accurate modelling of the road geometry and the derived geometric features for Advanced Driver Assistance Systems (ADAS). This offers new perspectives for Lane Departure Warning since precise positioning provides sufficient information for computing the offset of a vehicle from the road centreline, or from the boundaries of the lane.

Keywords

Road safety – Mobile mapping – Road geometry - ADAS – 5th Swiss Transport Research Conference – STRC 05 – Monte Verità

1. Introduction

1.1 Context of road safety

The reduction of road fatalities is one of the main objectives for all the European countries. The traditional accident prevention has been focused on the driver's behaviour and the improvement of passive safety in the vehicle, but these conventional safety measures are nowadays reaching their limits. New technologies are becoming available and with a potential to assist in decreasing the number of accidents. Innovative Intelligent Integrated Transport Safety Systems offer a great potential to address the road death toll. They involve an approach where active and passive safety measures, information and navigation technologies must play a significant role. Such an integrated methodology must take into account the driver, the vehicle and the infrastructure. As almost 95% of the accidents are due to the human factor, such assistance needs to be offered at given times. For this reason, Advanced Driver Assistance Systems (ADAS) favour the development of in-vehicle tools to warn the driver to take the appropriate decision. Numerous private and public initiatives are undertaken to deploy integrated safety solutions at a reasonable cost.

1.2 ADAS applications

A part of the integrated safety system, onboard ADAS, helps the driver to enhance the vehicle control. These systems use precise positioning sensors, mapping system, communications technologies and dedicated human interfaces for obstacle detection, collision warning and user protection.

An efficient implementation of the positioning component of ADAS should include an absolute positioning module (GPS/IMU[1]), close-range sensors and an enhanced mapping system. Depending on the ADAS application, the requirements for positioning accuracy may considerably vary. This application variability is essentially linked with the lateral and longitudinal

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[1] GPS: Golbal Positioning System (satellite-based system)
IMU : Inertial Measurement Unit (gyroscopes, accelerometers)

controls of the vehicle that have a direct impact on the geometric accuracy of digital road maps. A precise positioning of the road centreline, respectively the different lanes, is absolutely necessary for the deployment of ADAS applications with high requirements for the lateral control such as Lane Departure Warning, Collision Avoidance, Lane Keeping.

These accuracy requirements were proposed by both car and map manufacturers and were integrated within the NextMAP project that evaluates the technical and economical feasibilities of enhanced digital road maps. Two major mapping companies, Teleatlas and Navteq, have started to collect additional information with metric accuracy to reach the requirements for specific ADAS applications. New technologies, like mobile mapping, help reducing the cost of data acquisition and obtaining road coverage with enhanced precision and reliability. [Pandazis, 2002]

Figure 1 Example of ADAS application- Collision Avoidance

2. Road geometry

Numerous ADAS applications require a combination of precise positioning technology and enhanced map databases. Only accurate and reliable road data will convince users to claim the widespread use of safety applications. In this context, road geometry is one of the main features that has to be reliably described and measured.

The quality of the geometry includes the accuracy of the centreline, the topology of the road network as well as the frequency of the map update. The combination of these three factors guarantees the integrity of the road geometry for very demanding application. In this context, the Geodetic Engineering Laboratory of the EPFL implements a Mobile Mapping System (MMS), *Photobus*, for the fast acquisition of road geometry with a real-time data quality control. [Gilliéron, 2003]

2.1 Data acquisition

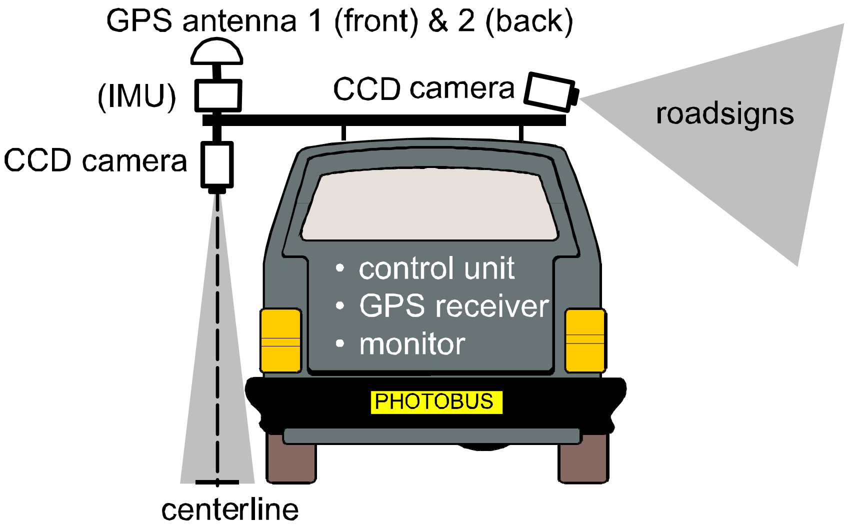
Photobus takes part in a more general study of road geometry. In its origin was the Swiss road and traffic association (VSS) that funds research activities in the field of road databases for maintenance. Its projects SYRROU and AGRAM have developed a general concept for the road geometry acquisition, modelling and management. In this context, several practical experiments were carried out to accurately measure specific road sections in rural, mountainous or urban areas of Switzerland. [Golay, 2002] [Merminod, 2003]

2.1.1 Mobile mapping system

MMS represents an advanced technique for the kinematic surveying of the road networks and all their surrounding objects. It provides a fast and accurate method to generate digital maps including both road geometry and features. MMS integrates most of the current surveying techniques, i.e GPS, inertial sensors, digital imagery and laser ranging.

Photobus combines an accurate positioning by GPS/IMU measurements with a vertically oriented CCD or CMOS camera. An embedded system guarantees the synchronization of navigation data with imagery. This system allows the precise surveying of the road centreline with a quality control of the positioning data in real time. [Gontran, 2004]

Figure 2 The *Photobus* system



2.1.2 Survey in Switzerland

The current mapping of the Swiss road network derives from aerial photogrammetry with a geometric accuracy of a few meters. Such data quality is comparable to the specifications of road databases (GDF – Geographical Data Files) included in current navigation system. Both Swiss Federal Office of Topography and map manufacturers have planned to provide better topological and geometric data for several purposes: land management, location based services, navigation, etc. These actors each aim at improving the accuracy and reliability of geodata is one of the goals to be reached in five years.

In this context, *Photobus* is the ideal surveying platform for evaluating the accuracy of road geometry in real conditions. Several tests were carried out and among these was the surveying of a 100 km long stretch on rural and mountainous roads in Canton Vaud. This set of road sections contains all types of environmental characteristics (open areas, forest, tunnels and mountains) and road layout (fast changing curvature, deep slope, straightaways, etc.).

Some road sections have been surveyed several times with different GPS constellations to determine the quality of positioning. The comparison between different paths gives a good estimation of the system accuracy. Subsequently, classes of different quality can be created for small road section (250m).

Figure 3 Quality analysis on a 40 km road section

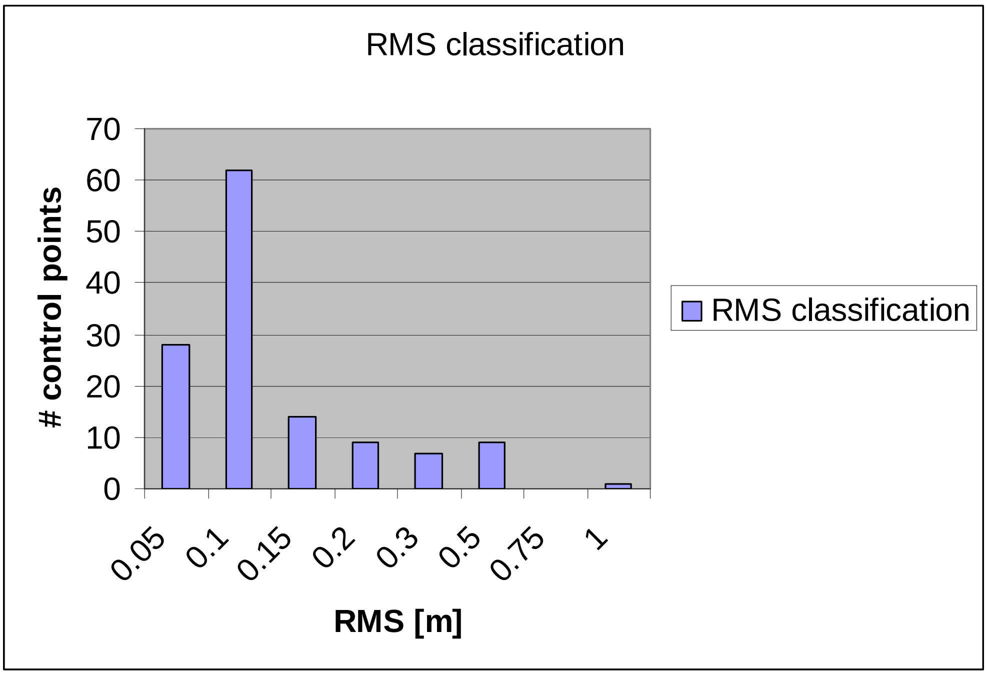


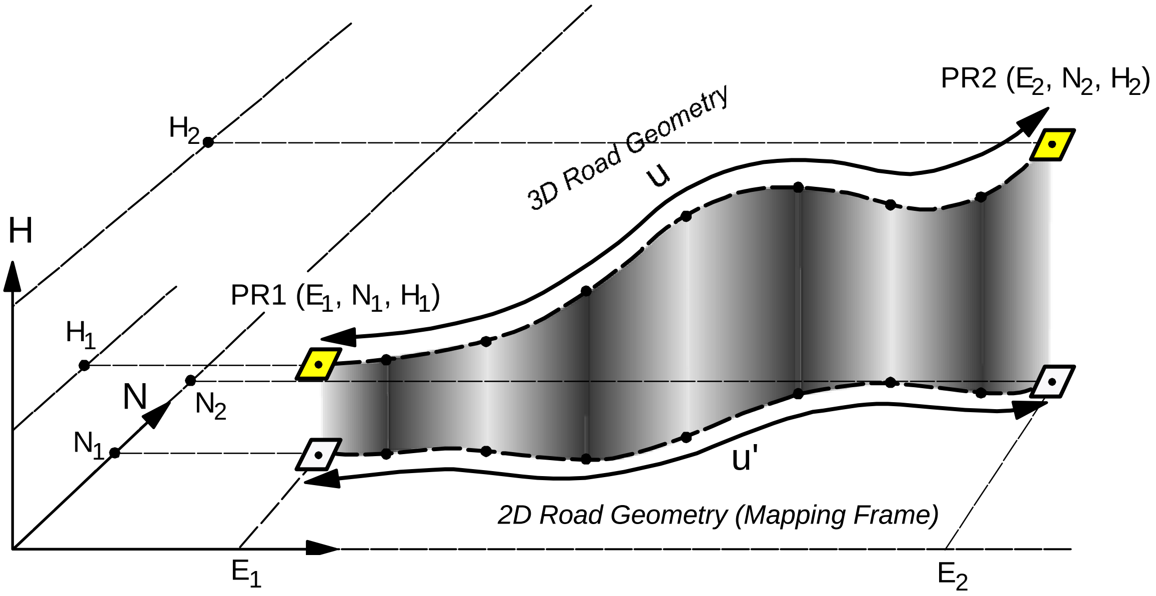
Figure 3 shows that most of the Root Mean Square (RMS) values are smaller than 50 cm, which is an acceptable limit for the road geometry in rural area. The average value of the geometric absolute accuracy is about 12 cm. This is a very promising level of precision for the development of demanding applications, however, few small sections where the RMS values are greater than 0.5m still remain. This is due to long GPS data outages and subsequent accumulation of inertial positioning errors.

2.2 Geometric modelling

2.2.1 Basic geometric model

The acquisition of the road centreline is a collection of points determined in a global reference frame, e.g. WGS84 for GPS. These geodetic coordinates are transformed in a local reference frame within a national grid system. This allows a separation of the horizontal and vertical components of the road geometry. However, the road design uses modelling of the centreline axis by basic 2D geometric elements (from straight lines to circles, via transition curves).

Figure 4 3D view of the road with the projection on the mapping plan



- E: Easting
- N: Northing

Figure 4 shows the relationship between 3D and 2D road geometry. Modern surveying techniques can measure points in 3D, and then perform the transformation to the final mapping model in 2D. Therefore, it is necessary to compute calibration parameters that are used such a transformation between 2D and 3D along the road axis.

$$Cal = \frac{u_{3D}}{u_{2D}}$$

Where: *Cal* is the calibration parameter
u_{3D} is the curvilinear distance in 3D
u_{2D} is the curvilinear distance in 2D

2.2.2 Centreline modelling by piece-wise splines

Photobus provides the coordinates of the road centerline in the Swiss local reference frame (E, N, H). To model and efficiently analyze the road geometry, we have to represent the road axis by interpolation functions, where the discrete points surveyed by *Photobus* operate as adjustment points. In a mathematical sense, a 3D curve is a differentiable function c from 3 to 3^3 so that:

$$c(t) = (E(t), N(t), H(t)) \qquad \forall\ t \in 3$$

Where $E(t) = c_1(t)$
$N(t) = c_2(t)$ are its Euclidian coordinate functions
$H(t) = c_3(t)$

We chose cubic splines to define the interpolants $E(t), N(t), H(t)$. Cubic splines are a piecewise interpolation by third-degree polynomials, between n-adjustment points. Consequently, they take into account all trajectory behavior on each piece of interval, while respecting continuity conditions on position, velocity and acceleration on each adjustment point. It can be shown that cubic splines minimize, among all interpolation functions, acceleration on the curve [Atkinson, 2002]. Considering these specifications, such curves are particularly well suited for road axis modeling in fast kinematic surveys. Finally:

$$c(t) = \bigcup_{i=1}^{n}\left\{E_i(t), N_i(t), H_i(t)\right\} = \bigcup_{i=1}^{n}\left\{a_i t^3 + b_i t^2 + c_i t + d_i,\ e_i t^3 + f_i t^2 + g_i t + h_i,\ j_i t^3 + k_i t^2 + l_i t + m_i\right\}$$

Where t is the GPS time,
a_i, b_i, c_i, d_i are the i-th cubic splines coefficients in the East direction and similarly e_i, f_i, g_i, h_i and j_i, k_i, l_i, m_i are the i-th coefficients in the North and vertical direction, respectively.

n: number of adjustment points

2.3 Road features

2.3.1 Radius of curvature

It has been observed that long straight tracks can be a source of accident, as they dull the driver or urge him to speed up. For this reason, it is recommended to alternate straightaways with long-radius and transition curves. However, most turns generate a decrease of speed and surprise the driver in case of bad visibility. An ADAS function, the Curve Speed Warning

(CSW), alerts users if they are travelling too fast to successfully negotiate an upcoming turn. Since road norms link a radius of curvature with a maximum speed, only an exact knowledge of these radiuses can make CSW reliable. The combination of accurate axis geometry with the proposed spline modelling achieves satisfactory results. With our spline parameterization, the 2D radius of curvature ρ is given by:

$$\rho(t) = \frac{\left(\dot{E}^2 + \dot{N}^2\right)^{3/2}}{\dot{E}\ddot{N} - \ddot{E}\dot{N}}$$

Where $\dot{E}, \dot{N}$ and $\ddot{E}, \ddot{N}$ is the first and second derivative of $E(t), N(t)$ with respect to t, respectively.

Local maxima and minima of a function are characterized by zero values and sign changes of its derivatives. To study the function describing the radius of curvature, we have therefore determined the analytical derivative of ρ as:

$$\dot{\rho} = \frac{\left[3 \cdot \sqrt{\dot{E}^2 + \dot{N}^2}\left(\ddot{E} + \ddot{N}\right) \times \left(\dot{E}\ddot{N} - \ddot{E}\dot{N}\right)\right] - \left[\left(\dot{E}\dddot{N} - \dddot{E}\dot{N}\right)\left(\dot{E}^2 + \dot{N}^2\right)^{3/2}\right]}{\left[\dot{E}\ddot{N} - \ddot{E}\dot{N}\right]^2}$$

Figure 5 Classification of a road sector from Canton Vaud by the radius of curvature

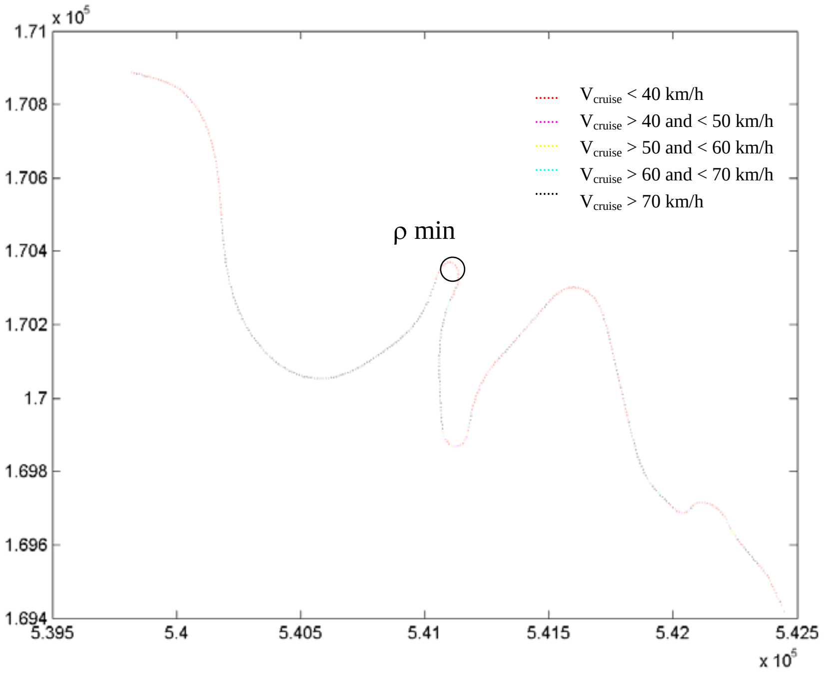


Figure 4 shows a classification of the road areas by the radius of curvature. This corresponds to the Swiss recommendations for the safest banking angle (7%). These recommendations directly link the radius of curvature with the cruising speed, so that ADAS can efficiently exploit this analytical modelling by warning the driver who is taking a turn too fast.

2.3.2 Longitudinal slope

The longitudinal slope is given by the first derivative of the above-mentioned third-degree polynomial *H(t)*. This indication is particularly useful when a user reaches a road sag or summit. It can help to adapt speed, or even the behaviour (for example, avoid overtaking) when the radius of the vertical transition curve does not provide good visibility in case of unfavourable weather.

2.3.3 Banking angle

In order to reduce the centrifugal force effect, the pavement is transversally leaned towards the inside of the curve, which reduces the danger of skidding. This road feature, called banking angle or superelevation, can be extracted from a close-range laser scanner. Since *Photobus* currently embarks sensors dedicated to a curvilinear description of the road axis, we take the safest and maximum value for the banking angle, i.e. 7%.

3. Concept for safety applications

3.1 Requirements for ADAS applications

We present two applications; the first one is dealing with Driver Assistance Warning in potentially danger situation; the second concerns lane keeping with high requirement for the lateral control.

3.2 Early Warning

The concept of Early Warning often implies radar coupled with a Variable Message Sign (VMS) to prompt a driver with reducing speed. Dynamic curve warning systems are more effective in encouraging drivers to comply with speed limits compared to static signs. They measure the speed of the vehicle approaching the curve and display a flashing message on the roadside VMS for the driver to slow down in preparation for the curve ahead. Onboard Early Warning Functions, due to their close interaction with the user, may even have a better impact on road safety. Gallet et al. (2000) recommend performing a warning if the deceleration needed to reach the cruise speed computed by the radius of curvature analysis is greater than 0.5 g. The minimum warning distance between the vehicle and the beginning of the curve is given by:

$$d = \frac{\left(v - v_{cruise}\right)^2}{2\gamma} + \tau v$$

Where v is the vehicle speed
v_{cruise} is the recommended speed derived from the radius of curvature analysis
γ is the deceleration (value of comfort: $2\mathrm{m.s}^{-2}$)
τ is the reaction time (value of comfort: 1.2s)

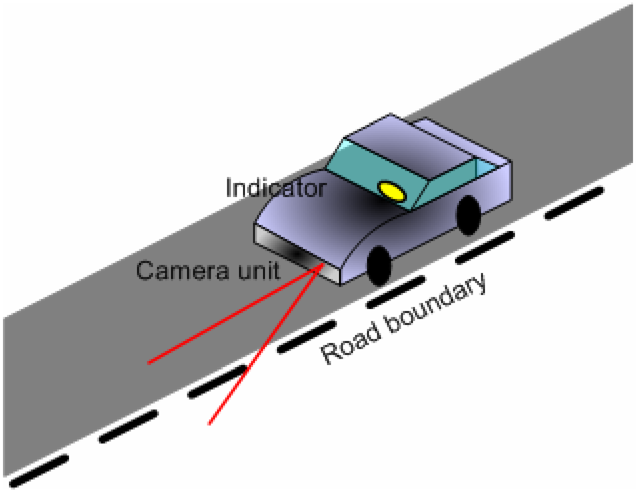
To illustrate the process, if the current speed v is 80km/h whereas the upcoming curve requires v_{cruise} = 60km/h, the driver should be warn 34m before the beginning of the curve.

3.3 Lateral control of the vehicle

Drivers can easily suffer fatigue or distraction, especially on long and monotonous journeys. The lane departure warning (LDW) helps by issuing a warning to the road user if the vehicle strays out of its lane. A fast-operating camera mounted inside the vehicle tracks the markings of the road ahead and defines a warning zone relative to this track. If the vehicle enters this zone, a warning is issued, allowing the driver to react before the situation becomes dangerous. Most LDW systems self-activate when the car reaches a predefined speed to prevent false and annoying warnings while parking or manoeuvring.

Figure 6 illustrates this concept. A small camera unit placed in the area of the windshield looks at the lane in front of the vehicle. Digital processing then calculates the position of the vehicle via digital image processing. Finally, a warning signal (acoustic or visual) is produced before leaving the lane, offering the driver to early avoid a hazardous situation.

Figure 6 A classical illustration of a LDW system



However, such a system only relies on close-range sensors and imagery to activate Lane Departure Warnings. This means that unfavourable weather or absence of markings may disable camera-based LDW systems.

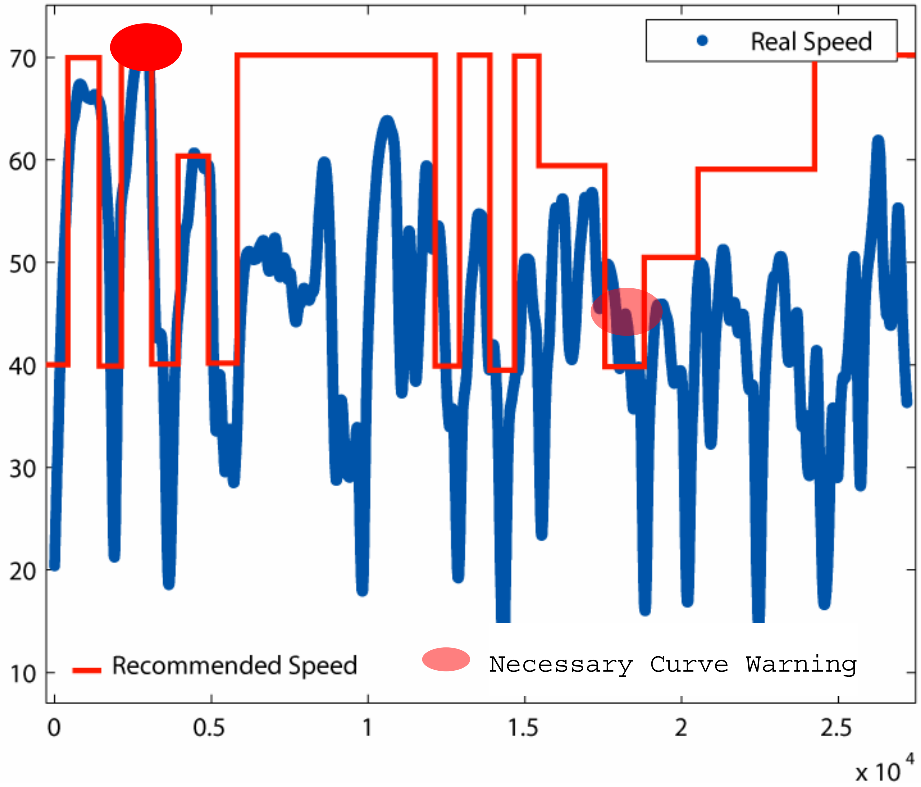
In a close future, satellite-based positioning will provide submetre accuracy via the new generation of GPS or Galileo satellites (GNSS 2). Such a positioning combined with a road database of similar or better accuracy (derived from a *Photobus* survey for example) represents a promising approach that extends the availability and the reliability of Lane Departure Warning. Under normal conditions, image processing can detect a tendency to leave the lane and such a tendency can be checked by satellite-based positioning. Moreover, future GNSS-based positioning will enable the computation of the lateral offset of the vehicle from the centreline of the road, so that LDW can be produced in the case of reduced visibility of the markings.

4. Use of road geometry in different applications

4.1 Curve warning and control

The road geometry is used to classify the road segments with respect to the recommended speed limit, on the trajectory seen in paragraph 2.3.1. In the following figure we recapitulate the real and recommended speeds along the whole trajectory to show where Curve Warnings should be issued. Such a graph is particularly useful to check the driver's behaviour in special conditions.

Figure 7 Real speeds and Curve Warnings



4.2 Lane departure warning

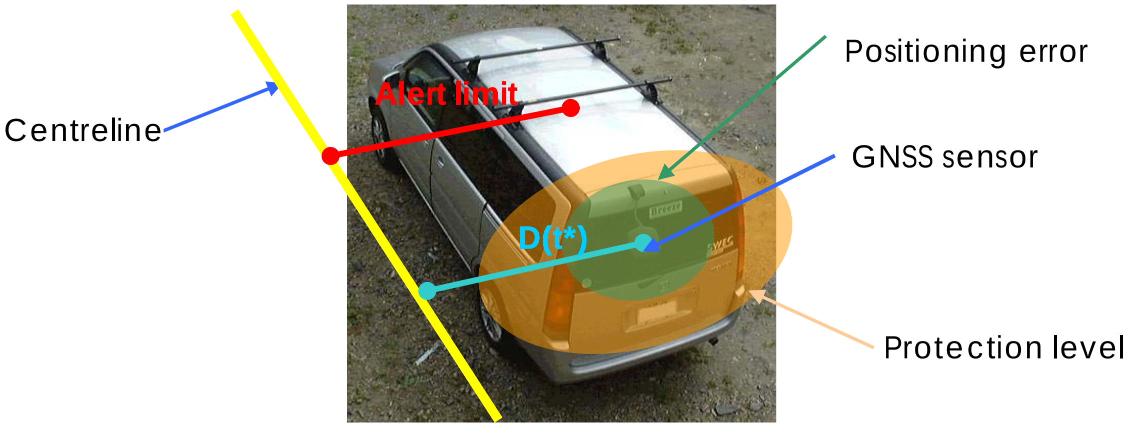
In practice, the vehicle position within the lane boundaries is constantly monitored. Real-time image processing of the road surface is the main trigger of Lane Departure Warnings whenever the associated algorithm indicates the absence of road markings. To avoid issuing false warning, satellite-based techniques have to confirm the trend towards leaving the lane. Since GPS localizes the vehicle with EN coordinates (E_v,N_v), it is necessary to determine the point (E_g,N_g) on the road geometry that is the closest to (E_v,N_v). This point on the road geometry will be defined using the GPS time t that parameterizes the spline model; and by the distance from (E_v,N_v) to (E_g,N_g), so called the *offset distance*. Given (E_v,N_v), we can identify the piece of spline to be considered for the offset computation. Then we have to minimize $D(t)$ such as:

$$D(t) = \left(E_v - E(t)\right)^2 + \left(N_v - N(t)\right)^2$$

If t^* represents the GPS time at which the minimum distance is reached, then $D(t^*)$ is the lateral offset whereas $(E(t^*), N(t^*))$ defines (E_g,N_g) and indicates the GPS-determined position of the vehicle relative to the lane boundary.

Embarking a vertically-oriented camera with accurate positioning sensors, *Photobus* is an ideal platform to simulate particular cases when LDW should be issued or not. A correct trigger of LDW is related to the concept of integrity, defined as the level of trust that can be placed in the information provided by the whole system. This concept includes the ability of the system to provide valid warnings in time to users when the system must not be used for the intended operation. For this reason, the half width of a lane was chosen as an Alert Limit (AL) to be compared with a protection level, id. a GNNS-2 compatible positioning error (circa 50 cm) affected by a safety factor (Figure 8).

Figure 8 Concept of integrity for Lane Departure Warning



The system behaviour can be summarised as follows:

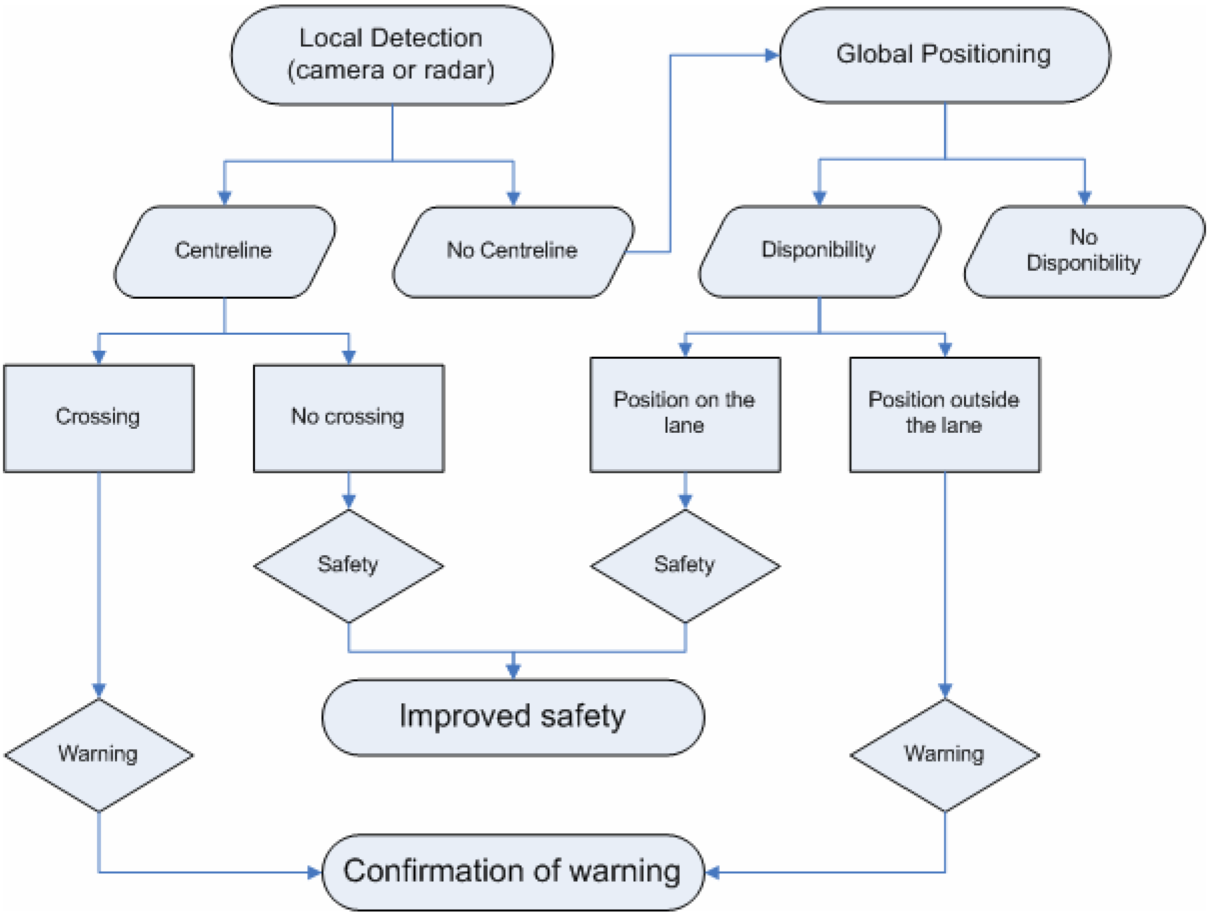
- If the Protection Level exceeds the Alert Limit, satellite-based positioning is not usable to issue a LDW and it hands over to image processing that may detect a lane crossing. In case of no marking, pattern recognition algorithms fail and the user is warned that the system cannot be trusted.

- If the protection level is similar to the Alert Limit, $D(t^*)$ is computed and GNSS sensors hand over to the camera. As soon as the video analysis detects a lane crossing on successive frames, a LDW is issued.

- If the protection level is significantly below the Alert Limit, no LDW is issued (safety criterion). Image processing may reinforce this safety criterion by confirming no crossing of the line.

The following scheme depicts the concept in detail:

Figure 9 Lane Departure Warning trigger



5. Perspectives

The paper discussed the dependency of ADAS implementation on accurate road geometry. However, as the road network rapidly evolves, the database related to the road axis needs to be frequently updated. In this context, many institutional and industrial actors investigate and develop mechanisms for dynamic updates of digital map in the vehicle. These mechanisms include all the steps for the collection, the management and the delivery of new road data via Internet-based technologies. The success of this dynamic update must be based on a high quality management.

MMS such as *Photobus* can play a leading role in evaluating the positioning quality of geo-data, a step that should be included in a certification process. Current developments focus on decreasing the time necessary to actualise digital map databases in the vehicle. With the sub-metre accuracy that is expected from the incoming satellite-positioning systems and the progress in image processing, ADAS-equipped vehicles will contribute to the detection of changes in the road databases, which will in turn improve the digital maps used for safety applications.

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