VEHICLE TRAJECTORY ANALYSIS: A NEW APPROACH OF ROAD SAFETY

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ABSTRACT

Road accidents kill 1.3 millions and injury 50 millions people/year worldwide. These figures increase in emerging countries, but decrease in developed countries thanks to progressses on vehicle, infrastructure and driver behaviour. However, 40 000 people are still killed on the European roads, and the EU intend to divide them by two by 2020. Because of the low rates of killed people per km.passenger, and of the multiple causes of an accident, the accident statistics alone are of very little use to support research aiming to further reduce the mortality. Therefore, research works were undertaken on vehicle trajectory modelling and measurement to evaluate interactions between vehicle, drivers and road infrastructure, and identify "quasi-accidents", as indicators of inappropriate driving behaviours or infrastructure risky zones, and thus increased risk. The trajectory means vehicle location, speed, acceleration and jerk, as time functions. Numerous technologies are available for trajectory measurement, used in roadside and on-board observatories. This paper shows the benefit of using trajectory observatories, their current limitations and perspectives of development, gives an overview of the available results on modelling and measurement techniques, from several projects supported by the National programme PREDIT, and reports some case studies for bends, intersections, and low volume roads.

1. CHALLENGE OF USING VEHICLE TRAJECTORIES FOR ROAD SAFETY

1.1. Road Safety Stakes

Road accidents kill approximately. 1.3 millions people per year in the world, i.e. 3,500 per day or one death every 25 seconds. Fifty millions of people are injured or disabled every year, 90% of them in developing countries. Children, pedestrians, cyclists and the elderly are among the most vulnerable of road users. The total road accident costs are evaluated between 65 and 100 billions US$ per year worldwide, i.e. 0.5 to 3% of the GNP depending on the level of motorization of the country.

Table 1 reports figures of road fatalities in most developed and BIC (Brazil, India and China) countries, reported by the World Health Organisation, and by the OECD if different. The cumulated fatalities per year in this table are just above 400,000, i.e. less than one third of the world total. Without the BIC countries, the total drop down to 182,000, and in the OECD countries to 120,000, i.e. less than 10% of the world total.

The differences between the WHO's and OECD's data underline the difficulty to collect reliable accident data, even statistics on fatalities (person died within 30 days after the accident), and other organisations such as the International Road Federation (IRF), the World Bank or the Transport Research Laboratory (TRL) in UK report other figures [1]. In many countries a large underestimation is made by the police and official statistics, such as -40 to 50% in Brazil and China, if compared to other sources of information [1].

Table 1 – Road Accidents Fatalities by Countries (WHO/OECD, 2004)

Country	Death Rate p.c.	Population (millions)	Number of Deaths	Country	Death Rate p.c.	Population (millions)	Number of Deaths
Netherlands	4.93	16.3	804	Hungary	12.96	10	1,296
Sweden	5.33	9	480	Turkey	13.0/8.0	68.9	8,957
United Kingdom	5.34/5.7	60.3	3,220	Czech Rep.	13.55	10.2	1,382
Japan	5.76/7.5	127.7	7,356	Belgium	14.2/10.9	10.3	1,463
Switzerland	6.85	7.45	510	Ukraine	14.51	48	6,965
Germany	7.09	82.4	5,842	USA	14.53	293.5	42,646
Australia	7.94/8.6	20.1	1,596	S. Korea	14.7	48.1	7,071
India	8.33	1,080.3	89,989	Poland	14.8	38.6	5,713
Canada	8.56	31.9	2731	Greece	15.27/13.5	10.6	1,619
France	8.67/9.2	60.4	5,237	Romania	17.42	22.4	3,902
Portugal	10.81/12.4	10.5	1,135	Malaysia	21.04	23.9	5,029
Italy	11.5/10.3	58	6,670	Russia	24.1	143.7	34,631
Spain	11.79	40.3	4,751	Iran	38.7	68	26,316
Brazil	12.8	180	23,040	China *	(8.26)	1,296.5	(107,091)

N.B. Figures are sorted by increasing death rate per capita (p.c.) given in deaths per 100,000 people.
The second figure of this rate is the OECD's one if significantly different from the WHO's one.
* It has been alleged that the road death rate p.c. in China is vastly higher than the official number given, hence the reason for it being posted at the bottom of the list.

There are large differences in the death rate per capita (p.c.), from 4.5 to more than 30 per 100,000 people, by region, type of countries and other factors. Moreover, the fatalities increase with the traffic volume in emerging countries, up to 20 to 25% over a ten year period, while the quick progresses on vehicle passive and active safety and on the infrastructures, combined to the driver behaviour improvement resulting from more education and penalties, reduce them by 20 to 40% over the same period in developed and OECD countries. However, 40,000 people are still killed on the European roads, and the EU target is to divide this figure by two by 2020.

1.2. Vehicle Trajectories and Road Accident Mitigation

Because of the low rates of killed people per km.passenger or by km of road, above all in developed countries where the most obvious causes of accident have already been prevented, and of the complex and multiple causes of an accident, the accident statistics alone are of very little use to support research aiming to further reduce the mortality and injuries. Therefore, LCPC (now IFSTTAR after the merging with INRETS on 1/1/2011) undertook since 2003 to carry research works on vehicle trajectory modelling and measurement, and on "near-miss" identification, as increased road risk indicators, inappropriate driving behaviours with respect to environmental and infrastructure conditions, or risky zones of the infrastructure.

The main idea is to develop a new concept of vehicle "extended trajectory", which is not limited to the vehicle path on the road, but comprises the vehicle 3-D location, speed, acceleration and jerk if needed, as time functions, or the vehicle coordinates and its time derivates until the second or third order. Detailed deterministic and probabilistic models of such trajectories are developed and implemented, to analyze and relate accurately the output of the vehicle-driver-infrastructure interaction, i.e. the trajectory, to the environmental and contextual parameters, such as driver behaviour, geometry or performances of the infrastructure (e.g. radius of curvature, slope, skid resistance, etc.) and of the vehicle.

Defective trajectories or trajectory failures are defined, with respect to pre-defined limit states or failure modes, to assess the level of safety or risk of numerous situations and scenario. Not only severe or true accidents are considered, but some frequent unsafe situations are taken into account in this safety assessment, as a risk indicator. E.g. a wheel encroaching on an emergency lane, an adjacent lane or a hard shoulder, is named a "quasi-accident", or "near-miss", and reveals a partial loss of control of the vehicle by its driver, and thus an inadequate speed, or command with respect to the road and vehicle performances and environmental conditions. Such events are not rare, and thus accessible to meaningful statistics, which allow forecasting and preventing more severe failures, i.e. accidents. These tools and methods lead to jump from a curative treatment of the road unsafety, e.g. black spot mitigation, after an accumulation of fatalities and injuries, to a series of preventive measures, such as driver warnings, self explaining road, dynamic road information, advanced driving assistance systems (ADAS), etc. The evaluation of these measures can be made by analyzing their impact on the rate of near-miss, or on the probability of failure with respect to such a failure mode. In addition to avoiding the need for many fatalities and injuries, the assessment is much more reliable by studying the reduction of a significant risk or probability of failure, let say in the order of magnitude of 10^{-1} to 10^{-3}, than working with much lower probabilities such as 10^{-4} to 10^{-6}.

Then, trajectory observatories are intended to provide, process and store objective and extensive measures and data of vehicle (extended) trajectories. Analysis of these trajectories can develop indicators on the dangerousness of the road infrastructure use. Several research projects have used this approach for bends, intersections, and low volume roads, such as the SARI programme of the PREDIT 3, and its related projects RADARR, VIZIR, IRCAD, etc. [2].

2. TRAJECTORY OBSERVATORIES AND THEIR APPLICATION

2.1. Trajectory Measurements and Observatories

The whole set of hardware and software tools to collect, process and analyze the data, described in the sections 3.2 to 3.4, are named "Trajectory Observatories", and then the databases of recorded trajectories by extension. Depending on the application and on the resources available, various measuring tools can be used. In most cases, the trajectory observation requires to combine several types of measuring devices, suited to the vehicle type and traffic conditions. Personal cars and heavy commercial vehicles behave differently, and therefore generate rather different trajectories. A vehicle can be "isolated", "free", belonging to a platoon, or constrained by other vehicles (Figure 1), according to the definition of the Glossary of Terms developed in this research [3].

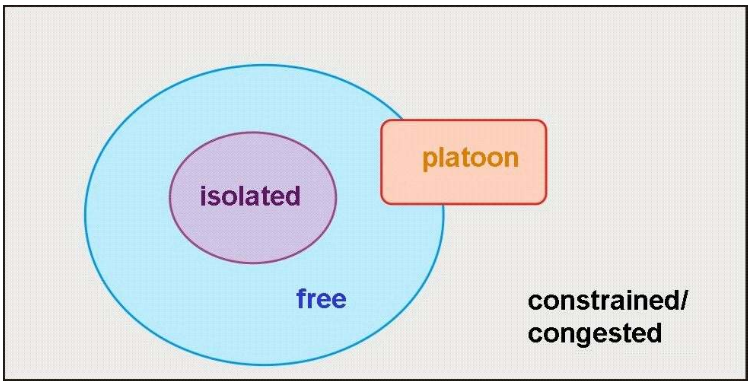

Figure 1 – Different vehicle situations in a traffic flow (CETE Normandie-Centre)

A vehicle trajectory analysis requires knowing the boundary conditions applied to this vehicle, i.e. the trajectories of the preceding vehicles, and the environment parameters, which may be recorded by a videocamera.

2.2. Types of Trajectory Observatories

Four categories of trajectory observatories were defined (Table 2), depending on the location of the measuring equipment (on-board of the vehicle or outside it), and on the scale of the trajectory measurement (local or global). The measurement scale depends on the type of tools used. On-board measurements are performed with instrumented vehicles, while external measurements are provided by roadside devices. Both systems are complementary:

- MITL/MITG: instrumented dedicated vehicles which deliver generally very detailed data (resolution, accuracy) for a limited number of trajectories of a limited sample of drivers;
- METL/METG: roadside tools which provide reduced quality data but for the whole population or a large set of the road users on a given road section (traffic micro analysis).

Table 2 - Classification of the Trajectory Observatories

	Internal (on-board) means	External means
"Local Trajectories" on limited spots < 100m	(1) Internal Measurement of Local Trajectories (MITL)	(2) External Measurement of Local Trajectories (METL)
"Global Trajectories" on itineraries > 100m	(3) Internal Measurement of Global Trajectories (MITG)	(4) External Measurement of Global Trajectories (METG)
"Reference Trajectory"	(5) Reference Measurement of Trajectories (MRT)	

2.3. Instrumented Vehicles (On-board Observatories)

These kinds of vehicles can be of different type, depending on the objective, from the heavily equipped ones, dedicated to accurate studies, which are generally unique given their cost, to the lightly equipped ones which can be duplicated under a very high number, like in the Field Operational Test (FOT) projects of the EU. We can list:

- a reference trajectory measurement equipment (MRT), which can be installed on any vehicle and has been designed to obtain very high performances (see section 3.3),
- heavily instrumented vehicles, combined with vehicle dynamics simulation software, dedicated to extreme driving behaviours estimation and “borderline trajectories”,
- moderately equipped vehicles to measure trajectories in current driving situations, generally used for local trajectories, but also for global ones,
- lightly (and as unobtrusive as possible) equipped vehicles, to be implemented on large vehicle fleets, for naturalistic driving experiments, mainly useful for global trajectories.

The first two types of equipped vehicles are generally unique in a research institute and driven by specialized drivers, the 3rd type is likely to be duplicated up to a few units, the 4th type up to several tens or even hundreds of units. Both of the last two types are driven by a large panel of drivers, i.e. a representative sample of selected drivers for the 3rd type, a very large sample of common drivers for the 4th type.

2.4. Road-side Observatories

There are also different types of road-side systems, such as: (i) microscopic traffic analysis systems, (ii) traffic conflict detection systems, and (iii) local trajectory measurement systems.

(i) Microscopic traffic analysis systems

These systems have been designed to accurately analyse the traffic flow. They are generally capable of measuring, at several locations:
- the lateral position of the vehicle, at least the lane which it is driving in,
- the speed,
- the category of the vehicle,
- the time and consequently the inter-vehicle time.

These systems are generally implemented for a specific driver behaviour study, either on a given stretch of road (typically a few kilometres), or on a localised black spot. They can be classified into class (2) or class (4) of observatories, according to Table 2.

(ii) Traffic conflict detection systems
These systems are designed for a specific application, i.e. to detect local conflict situations between vehicles, generally in intersection. They provide information such as:
- speed of the vehicles,
- time-to-collision,
- risk index,
- video recording of the hazardous situations, etc.

This information is valuable for the road manager to understand the hazard risk of the black spot and evaluating the benefit of modifying the infrastructure. The risk index allows cross comparisons between different intersections or black spots. An example is given in section 4.2.

(iii) Local trajectory measurement systems
These systems are dedicated to black spot studies, e.g. a hazardous bend. They are designed to record, as accurately as possible, the full trajectories of all passing vehicles, in order to detect the abnormal behaviours, revealing a dysfunction of the road-vehicle-driver system. More information is given in the section 3.5 and an example in the section 4.1.

3. TRAJECTORY MODELS AND MEASUREMENT TOOLS

3.1. Trajectory Modelling and Limit States

A vehicle traditional trajectory is a continuous function $\tilde{F}(t)$: $R^+ \rightarrow R^3$ (resp. R^6), which represents the vector of the 3D space location of the vehicle centre of gravity (resp. centre of gravity and Euler's angles) at any time t. The vehicle is represented by a mass point (resp. an oriented vector with a mass). The "path" represents the print of the trajectory onto the R^3 or R^6 space, without any mention to the time.

However, to address the road safety issues and perform more detailed analyses of the vehicle-driver-infrastructure interaction, it is necessary to consider also the derivatives (at the order 2 or 3) of this vector, i.e. the vehicle speed, acceleration and jerk for comfort studies. Thus the "full trajectory" F(t) is a function: $R^+ \rightarrow R^9$ or R^{12} (resp. R^{18} or R^{24}), with components which are not independent, but linked by derivation formula. These components explicitly appear in the safety or comfort limit states.

Because of these relations between the components of F(t), and also because these components must satisfy some additional equations of the kinematic and some boundary conditions, the so-called admissible trajectories belong to a sub-set of the real multidimensional space, i.e. a variety (e.g. a curve, a surface, etc.) of R^n.

A metric in the trajectory space is needed to compare trajectories, to identify safe or unsafe trajectories with respect to some limit states and safety domains. This issue is not obvious, because the Euclidian distance in R^n is not suitable. For example, if considering the trajectory of a first vehicle $F_1(t)$, and the trajectory of a second vehicle $F_2(t)=F_1(t+h)$, where h>0, the Euclidian distance $||F_2(t)-F_1(t)|| = ||F_1(t+h)-F_1(t)||\neq 0$, while the two vehicles have exactly the same behaviour, with respect to their location, speed, acceleration and jerk as time functions, only with a time shift. Hence, an adapted distance shall give $||F_2(t)-F_1(t)||=0$ in this case, but shall also distinguish two trajectories which have the same path (in space), but not the same time history. Investigations were carried out in the literature, and a Mahalanobis distance was chosen [4]. This distance is based on the correlation between variables, and is efficient to determine the similarity between two series of data. While the Euclidian distance gives the same weight to all the components of a vector, this distance under weighs the noisiest components (for Gaussian variables).

Limit states were defined, as the possible failure modes of a vehicle trajectory. As in structural safety, we introduced the ultimate limit states as non reversible limits, i.e. accident with more or less severe damages to the peoples and/or the vehicle. That is the case of collisions with fixed obstacles, with other vehicles or pedestrians, or of full lane departures. Among these accidents, only a few proportion lead to fatalities or severe injuries, and are accounted for in the road safety statistics. That is a first improvement to fill the gap of the road safety statistics, but it is not enough in developed countries where road safety policies and regulations, incl. checks and penalties, already reduced the accident rates at very low levels. Therefore, serviceability limit states were introduced, as events which reveal unsafe behaviours or nearly missed accidents (quasi-accidents), but are fully reversible, do not induce any damage to the vehicle, the infrastructure and obviously to the people, and even are not traceable without a specific instrumentation. Encroaching on an emergency lane, short skids or lateral acceleration in excess with respect to safety or comfort criteria are among these serviceability limit states. These events are much more frequent than accidents, by an order of magnitude of 1000 to 100,000, and thus, if properly recorded and analyzed, may provide much more reliable databases and background for accident prevention and road safety improvements.

The aim of the trajectory analysis is to relate the failures with respect either to the serviceability or the ultimate limit sates, or to the infrastructure, vehicle and driving command characteristics, as well as to the environment parameters (visibility, weather conditions, etc.). Sensitivity studies were carried out or shall be carried out to point out the most effective measures on infrastructure development, vehicle design and maintenance, and driver behaviour (education, information) to reduce the risk of failure [2].

Because there are a number of random parameters in road and vehicle engineering, but above all in the human factors and behaviour, a probabilistic approach of the trajectory analysis was also developed. Trajectories were modelled as stochastic processes, using either the reliability theory tools [5] for some governing random variables with which the limit states can be formulated, or some advanced probabilistic tools of the stochastic process theory and random process classification [4], in order to assess the probability of failure, and then the risk, taking into account the consequences of the failure.

To calibrate, validate and feed these models of trajectories, extensive and reliable data are needed (see the section 3.3). Then the models are used to perform simulations with a variety of scenarios which are impossible to observe or record on the road networks, or even on test tracks, above all near the ultimate limit states, which is very useful to assess low probabilities of failure.

3.2. Required Data and Measurement Methods

As explained in section 3.1, a full trajectory is composed of a time tagged set of 3D positions and (possibly) attitude angles of the vehicle, those angles being generally depicted as: heading (or direction), roll and pitch. For road safety analysis, there is no particular interest in measuring and analysing the elevation coordinate. Moreover, roll and pitch angles are not considered here, because we do not analyse the vehicle dynamics, and the roll-over failure modes are not in our scope. Thus, the X-Y coordinates of the vehicle centre of gravity and possibly the vehicle direction in its horizontal plane, are sufficient for our purpose. Even if from the X-Y coordinates (and potentially the heading) as functions of time, the successive derivatives known as speed, acceleration and jerk, can theoretically be derived if the data acquisition frequency is high enough, it is in practice very tough to obtain good data that way and any possibility to measure directly speeds and accelerations must be considered.

Therefore, the parameters to be measured are mostly:

- 2-D location on the road, i.e. the longitudinal abscissa of the vehicle and its lateral abscissa with respect to the central axis of the lane or road,
- direction (or heading) angle,
- longitudinal speed,
- longitudinal and transversal accelerations.

Table 3 – Relative interest of measurement technologies versus trajectory parameters

Parameter	Technology	GPS	IMU*	Image processing	Radar	Lidar
Plane position	On-board	xxx	xx	xx	x	x
	Road-side			xx	x	xx
Direction angle	On-board	x	xxx	x		
	Road-side			x	x	x
Longitudinal speed	On-board	xx	xxx		x	x
	Road-side			x	xx	x
Accelerations	On-board		xxx			
	Road-side				x	

Legend: x = low interest, xx = medium interest, xxx = high interest, otherwise = no interest
* Inertial Measurement Unit

The required sufficient set of parameters, as well as their quality, highly depends on the goal of the study. Various technologies can be used, depending on the application, the class of the observatory (on-board or road-side) and the available means for the study. Table 3 presents some relevant technologies for trajectory parameter measurement. The next sections introduce measurement systems and methods for various applications.

3.3. Reference and Calibration Tool

To calibrate and validate the trajectory models described in the section 3.1, we need samples of trajectories accurately measured, without any significant bias, error or noise. Such accurate and reliable trajectory samples and measurements are also required to calibrate common and operational trajectory measuring tools. Therefore, a high-grade measurement system, the MRT (Reference Measurement of Trajectories) was developed by the IFSTTAR. To get the best completeness, accuracy and frequency sampling of the measurements, a vehicle was equipped with an embedded system hybridizing a dual frequency kinematic GPS receiver and an inertial measurement unit (IMU).

The kinematic GPS ensures the absolute accuracy of locations and speeds, and the IMU perform the short-term filtering and guarantees the output rate and the continuity in case of GPS outages.

The IFSTTAR owned MRT was used in several research projects since late 2008. The basic equipment (IMU and software) is marketed by the French company IXSEA under the trade name ®LandINS, hybridizing a high grade IMU with optical fibre gyroscopes, the vehicle odometer and phase differential dual frequency GPS receivers (Figure 2). It can be used in real-time or in post-processing mode. In this latter mode the performances are twice better in case of long GPS outages, because the data can be processed in reverse time. The system is described in [6] and its main performances are presented in Table 4.

Table 4 - Main performances of the MRT and ®LandINS system

	Accuracy (RMS error)	
Trajectory parameter	when GPS is available	after 2 minutes of GPS outage
Heading, roll and pitch angles	0.01°	
Horizontal position	3.5 cm	15 to 30 cm *
Vertical position	5 cm	10 to 20 cm *
Speed (in any direction)	2 cm/s (0.07 km/h)	

* in post-processing or in real-time

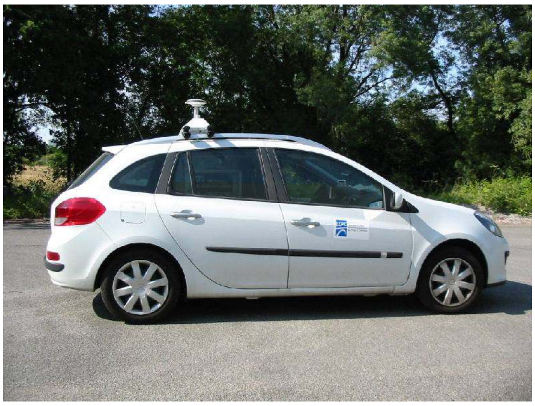

Figure 2 - The ®LandINS system embedded in the test vehicle VERT owned by IFSTTAR

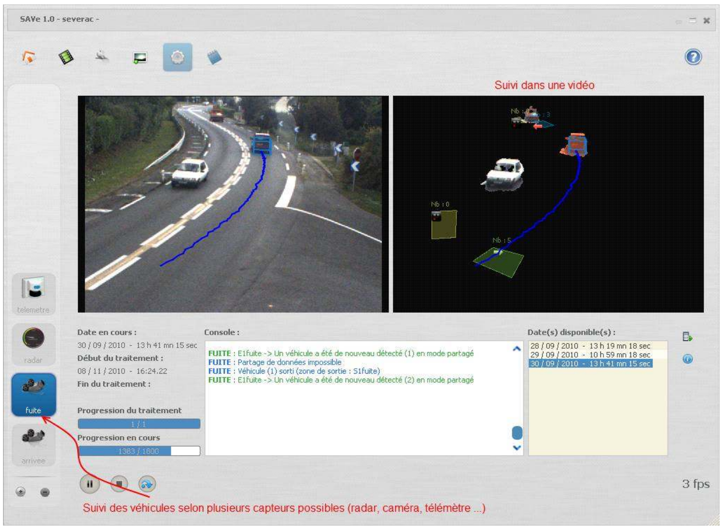

Figure 3 – Processing software of the trajectory observatory for safety diagnosis of local black spots

3.4. Extreme Driving Behaviour Estimation Tool

This road infrastructure diagnosis tool is an instrumented vehicle (Renault Laguna owned by the CETE of Lyon), which records the dynamic behaviour of a passenger car (location, speeds, accelerations) and the commands really applied by the driver on each itinerary. It is coupled to a numerical advanced simulation software (Callas), which simulates borderline driving situations. The combination of these both tools allows assessing the borderline trajectories on various infrastructure sections. It is a MITG, or class 3 trajectory observatory tool.

This instrumented car can perform one or more runs on an itinerary to be scanned, and all the data describing the vehicle behaviour are recorded. These data and the infrastructure characteristics, measured with a highly productive tool such as the VANI (Véhicule d'ANalyse d'Itinéraires), feed then the model Callas. Numerical simulations led to define speed thresholds to assess the user risk, by comparing these thresholds to the real or prescribed (by road signs) speeds. The model also allows to simulate driving situations by modifying the road infrastructure characteristics, e.g. the transverse slope in a bend, or the traffic conditions, e.g. by reducing the road skid resistance to simulate deteriorated weather conditions.

3.5. Local Safety Diagnosis Tool

If the purpose of the trajectory observatory is to analyse the trajectories of all the vehicles passing a suspected black spot to be diagnosed, e.g. a hazardous bend or an intersection, the observatory must be bound to the infrastructure, and then belongs to class 2 family of observatories (METL). GNSS technology is useless in this case, and the system must use remote sensing technologies.

Some very sophisticated military radars are capable of tracking several moving objects and of determining their trajectories, but not accessible to civil users because of their cost. The affordable technologies are: video cameras with image processing and laser range-finders (also called lidars), both being complementary. The lidar mainly tracks the vehicles in the bend, and the video cameras monitor the bend entrance and exit. A processing software computes the trajectories in post-processing mode.

It is difficult to measure the trajectory of each vehicle crossing the equipped road section and passing in the sensing area, and that requires advanced algorithms. The local trajectory observatory developed by the IFSTTAR and the university of Clermont-Ferrand, in the French SARI/RADDAR project in 2007 [7], uses a particle filtering method, and a vehicle “bicycle” propagation model. The particles represent the vehicle possible estimated locations, which are updated at each measurement time with a maximum of likelihood method, by updating the weight of each particle. The display screen of the software is given in Figure 3. Assuming that the observed vehicles belong to some predefined classes of specified dimensions and geometry, the performances of this observatory are presented in Table 5.

Table 5 - Main performances of the IFSTTAR local trajectory observatory for black spots

Trajectory parameter	Assessed performance	
Range	> 100 m	
Lateral location	Mean error: 20 – 30 cm *	Std Deviation: 10 cm - 20 cm *
Longitudinal speed	Mean error: 1.3 km/h	Std Deviation: 1.9 km/h

* depending of the type of bend

3.6. Itinerary Safety Diagnosis Tool

To perform the diagnosis of a whole or long itinerary with respect to the driver behaviour, it is not possible to equip the roadside all along the itinerary. The measuring equipment must be on-board the vehicles. In order to assess the itinerary safety, to identify the most hazardous sections and to derive some safety indicator, trajectories must be recorded and analyzed for a large enough sample of drivers, representative of the whole driver population. Therefore, a dedicated fleet of vehicles frequently circulating on the itinerary, shall be equipped and the trajectory data gathered in the context of “naturalistic driving”, to avoid any bias of the driver behaviour, which could be introduced if some drivers would be appointed to perform the measurements.

In addition to the trajectory parameters, such an analysis requires additional information on the driver's behaviour and environment E.g., a sudden deceleration or trajectory discontinuity can be caused either by a road defect or by another vehicle or mobile obstacle to be avoided. The context shall be known to avoid misinterpretations.

The trajectory parameters are measured with tools similar to those described in the section 3.3, but simplified and much less expensive. GPS and inertial technologies are the most concerned, and the system developed at IFSTTAR uses a video camera and image processing software to improve the accuracy in some area where an accurate road mark map is available. Thus, this system is based upon sensor data fusion software and its components, hardware and software, are:
- a fusion algorithm based upon an extended Kalman filter, using a standard “bicycle“ propagation model and GPS fixes (1 Hz sampling frequency) or lateral distances to the road marks computed by an image processing algorithm (images available every 5 m), to update the a priori estimate;
- a low-cost mono-frequency GPS receiver, providing the code and phase observables on L1, enabling a so-called kinematic phase-processing, to get a better location accuracy than a simple code-based solution.

The data fusion algorithm is described in [8]. The performances of the prototype system are given in Table 6.

Table 6 - Main performances of the IFSTTAR itinerary observatory

Trajectory parameter	Assessed performance
Range	No limit
Lateral position	10 - 20 cm RMS * (where road marks data are available)
Longitudinal speed	1.5 km/h RMS

* Depending on the type of road (straight line or bend)

4. STUDY CASES

4.1. Alerts in Bends

In France, on rural roads in 2009, crashes in bends accounted for 32% of accidents and 36% of fatalities, and thus are an important issue of road safety for road managers. Recently two research projects [9, 10], were completed within the SARI programme, on the safety improvement in bends. They delivered new devices for bend signing (Figure 4). Trajectories were recorded and analyzed to assess the impact of warning signal on the driver behaviour, by quantifying the trajectory risk. The location in the traffic lane, the speeds before and in the bend, and the lateral and longitudinal accelerations were measured. The limit states, derived from previous studies of accident statistics related to driving behaviour, were chosen as the combination of:
- deceleration: speed before the bend - crossing speed = 40 km/h
- lateral acceleration = 5m/s ²
- longitudinal acceleration = 5m/s ²
- maximum change in lateral acceleration
- vehicle position at the limit of the lane.

In the first part of the RADARR project [9], trajectories were measured to design the warning sign system. An instrumented vehicle (MITL type) was used to assess the limits for crossing the bend and provide the warning sign threshold. Runs at increasing speed were made by a professional driver.

Figure 4 - IRCAD warning signs

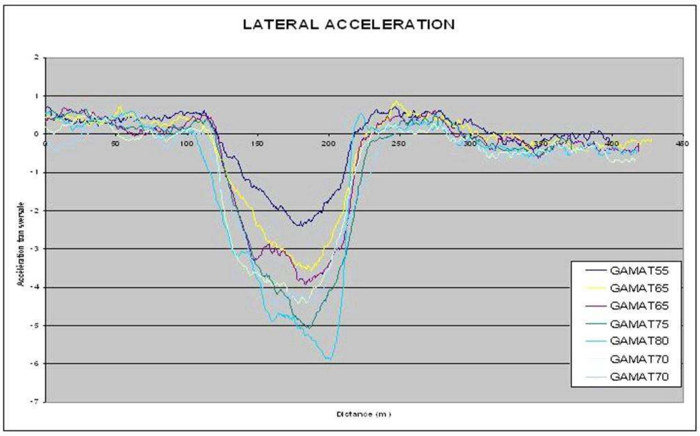

Figure 5 - Lateral acceleration for various speeds

The trajectory analysis (speed, lateral acceleration and locations) led to chose the optimal location for speed measurement to allow the too fast drivers to safely decelerate prior to the bend, and the speed threshold, to trigger the warning light and to keep the lateral acceleration below 5m/s ² (Figure 5).

The local roadside trajectory observatory (METL, section 3.5) was installed to collect the set of all users' trajectories (Figure 6) and compare them with those of the instrumented vehicle. Then the alert threshold was adjusted. These two complementary approaches led to alert about 15% of the drivers on this site. Only drivers who drove above the V85 speed before the bend were alerted.

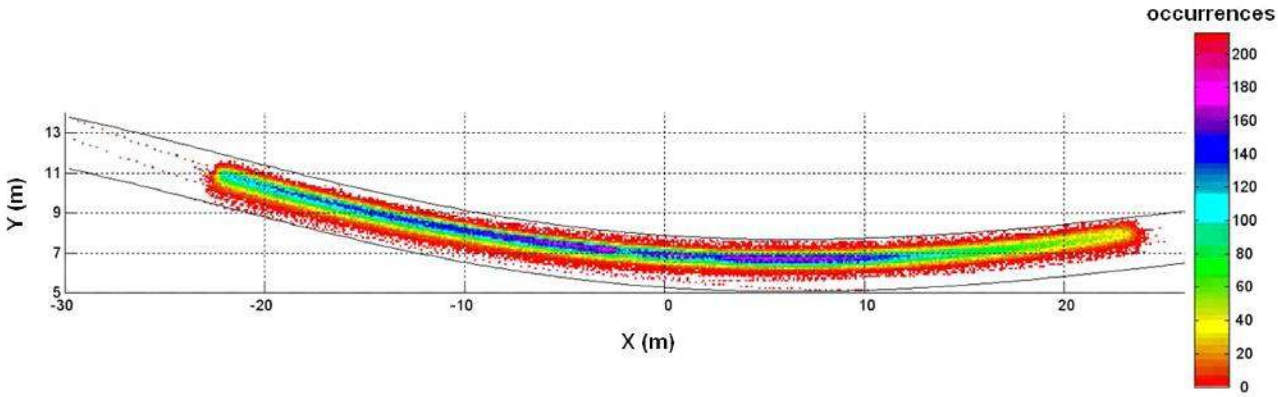

Figure 6 – Vehicle trajectories in a bend

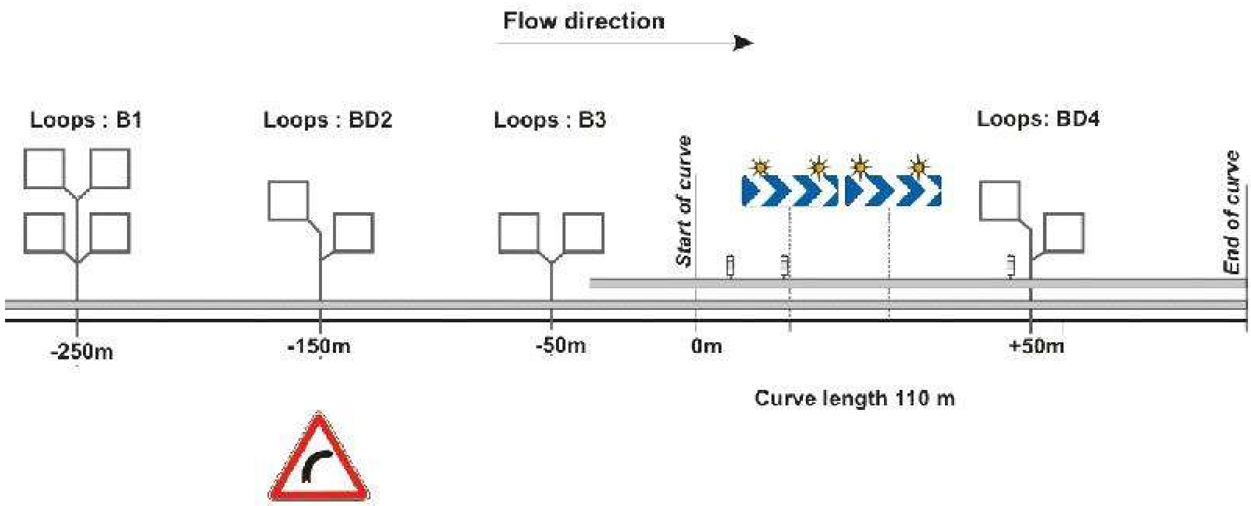

Figure 7 – Signs and loops location prior and in the bend

During the two project phases (before and after installation of the warning signs), trajectories were collected with a microscopic traffic analysis system (see section 2.4 (i)) using four sets of electromagnetic loops, installed as shown in Figure 7. Speeds and locations of free drivers were recorded. The four speed measurements were used to identify the passage of each vehicle and to reconstruct individual trajectories (Figure 8). Their analysis allowed quantifying the impact of the warning signs on the alerted drivers, who reduced their speed (Figure 9). This targeted slow down manoeuvre reduces the risk of fatality by an estimated 25%.

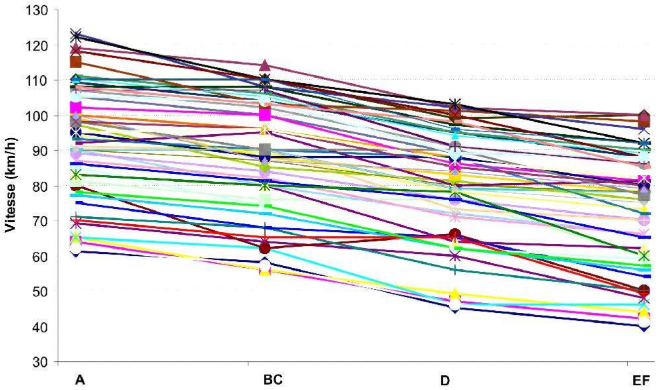

Figure 8 – Individual speeds in the bend

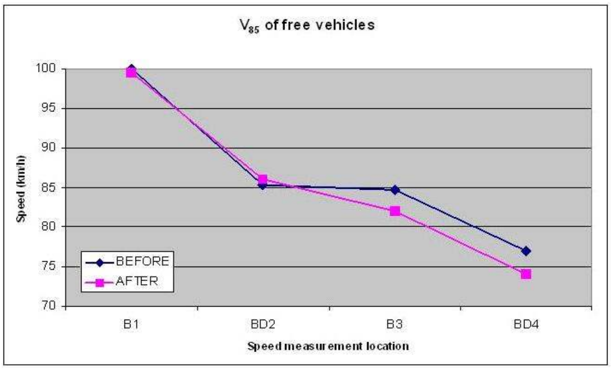

Figure 9 – Alert signs impact on V_{85}

4.2. Risk Mitigation in Intersections

Road intersections in France concentrate 10% of accidents and 13% of fatalities. The risk of an accident for a user travelling on a rural road, is multiplied by 10 at an intersection. Therefore, road managers are deeply concerned with this road safety issue.

The most frequent accident occurs when a non-priority vehicle enters an intersection and is struck by another vehicle travelling on the main priority road (Figure 10). The main causes of these accidents are:

- over speeding of the vehicle on the main road,
- lack of visibility.

However, the analysis of these accidents, which remain rare in a given intersection, does not help to improve intersection safety. The trajectory analysis and quasi-accident (also called “near-miss”) detection are necessary to estimate the risk as accurately as possible.

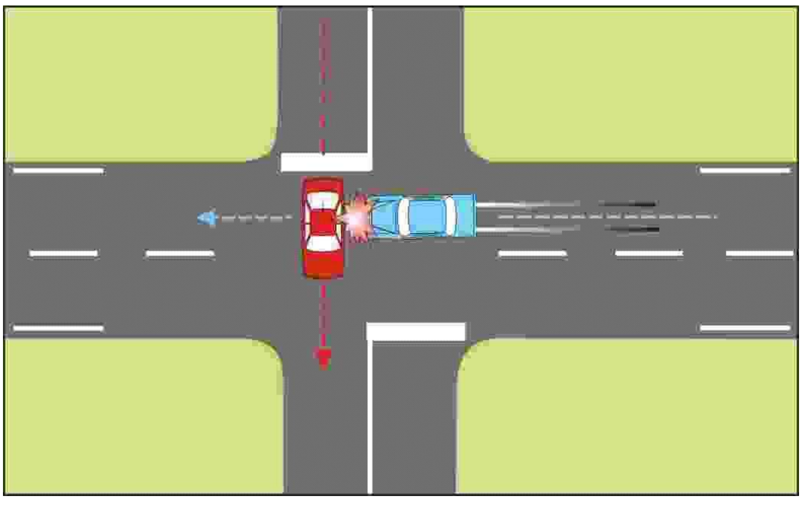

Figure 10 – Main type if accident in intersection

A “near-miss” is a traffic conflict described as: “an observable situation, during which two drivers approach one to another in time and space, to a point where there is a risk of accident if their movements remain unchanged" [11]. Near-miss detection is an application of local roadside trajectory observatories (METL). In this case, potentially risky situations are identified from predefined trajectories (Figure 11).

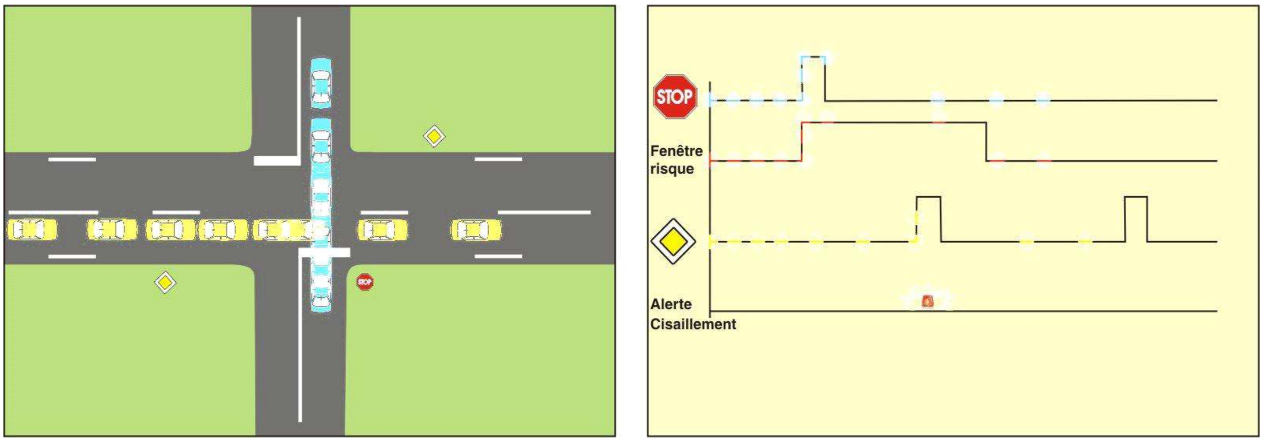

Figure 11 - Principle of the near-miss detection system

A system [12] was developed to detect and record conflicts between users from non-priority road and users of priority road, in motion. The system uses standard traffic sensors: Doppler radar on the main road and pneumatic tube at stop lane. It is settled at the edge of the road and delivers information on detected events: run timestamp and vehicle speeds. Then the time to collision is calculated and compared to a threshold, e.g. the time to cross the main road which is more than 6 seconds for a 2 lane highway. A video sequence is stored (30 seconds before and 15 seconds after detection). Finally a risk index is developed. Figure 12 gives an example of a detected near-miss accident.

Figure 12 – Example of a near-miss detection (source CETE Normandie-Centre)

4.3. Impact of Speed Enforcement Policy

International studies [13, 14] have shown the link between driving speed and accidents. Speed enforcement is a crucial security issue for public authorities and road managers. Late 2003, the French government has deployed an automated speed enforcement system, which was launched with a large media communication. Its implementation has led to a significant road safety increase. Assessments of user driving behaviour changes were carried out at three levels [15]:

- nationwide: on the whole territory using national surveys,
- locally: by regions using traffic measurements,
- individually: with radars by microscopic analysis of the traffic.

Roads in Normandy are equipped with traffic monitoring systems for statistical purposes (Regional traffic observatory). These systems also deliver speed measurements (distributions). Every day about 60 such systems provide speeds of more than 400,000 vehicles, used to assess the rate of over speeding vehicles. This indicator is used to assess the impact of automated speed enforcement tools and policy.

The over speeding rate was surveyed over a period of 5 years before and after the implementation of the speed enforcement. Figure 13 illustrates the speed and accident evolution over this period. It shows:

- a significant reduction in speeding and accidents,
- the impact of automated speed enforcement since it was announced (late 2002) and later reinforced (late 2003).

The local impact of an automated speed camera was evaluated by a microscopic traffic analysis, combining two (external local and global) trajectory observatories (METL/METG), over a section of several kilometres prior and after the radar. The speed and inter-vehicular time were analysed. Each speed camera (Figure 14) is preceded by a warning sign to drivers (Figure 15).

Ten traffic analysers were implemented over 13 km, from the warning sign, 1 km prior to the radar, until 12 km after the radar. Data were recorded during one year before and one year after commissioning of the radar.

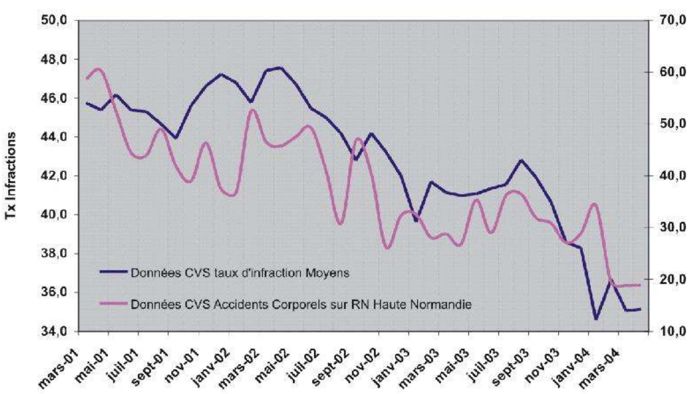

Figure 13 - Time evolution of speeds and accidents between 2000 and 2005 in France


Figure 14 - Speed camera

Figure 15 - Speed camera warning sign

The radar impact assessment was carried out using the speed violation rate by analysing:
- the transition during the installation of the radar,
- the significant reduction in speeding.

It was shown that the local influence of a speed camera is limited to about 1 km. However, there is a global awareness of the speed reduction benefit for road safety, provided by communication campaigns. That is quantified by the average speed reduction at regional and national scales.

5. CONCLUSIONS

The concepts, methods, measurements tools and technologies, and finally applications of the full trajectories, the quasi-accidents or near-miss, and the trajectory observatories, developed along the last decade by the IFSTTAR (ex LCPC) and its partners, provide a very effective approach to improve the road safety. This allows analysing very accurately interactions between vehicles, drivers and road infrastructure, and the driver behaviour's fit or discrepancy with the vehicle and infrastructure characteristics in a given environment and particular traffic conditions. Using serviceability limit states, which correspond to quasi- (or near-missed) accidents, and therefore are much more frequent and no damaging, indicators of inadequate behaviours or risky zones of the infrastructures are build. Extensive data can be gathered in naturalistic driving conditions for large driver samples, either by roadside or on-board, and local or global, trajectory observatories, of by a heavily instrumented vehicle to collect more detailed and specific data. That opens new perspectives to further reduce the accidents rate by preventive methods, rather than using a posteriori fatalities and injuries statistics. This approach will be of particular interest in developed countries and everywhere, when the conventional measures (e.g. speed enforcement, driver education, safer vehicles, improved infrastructures) are already implemented. Such an approach may also be very cost effective, avoiding a significant amount of accidents and affordable means, but also environment friendly, avoiding some heavy road works and congestions.

New prospects are interesting and their development is encouraging to acquire new knowledge.

Concerning on-board systems, the implementation of instrumented vehicle fleets at low cost and of naturalistic driving depends on the car manufacturers development projects, such as European FOT projects, and will require to process very large amount of data by data mining techniques. A similar approach could be conducted by European research organisations, like SHRP2 project in the US. A new project is starting in France (SVRAI) to collect data on near-miss or on situations near the limit states by using event data recorder, built on a partnership with local road managers. Large fleets of instrumented vehicles are a new challenge for increasing knowledge of driving activity in relation with road safety.

Concerning roadside devices, the roadside trajectory observatories and external measuring tools developed by IFSTTAR, now can monitor all the vehicles over 100 m in length zones. However, the quality of the data may still be improved. Beside the speed, more parameters will be needed to carry out deeper analyses.

Finally, the driver shall not be forgotten, as the key actor of the whole system: "always keep the driver in the loop !". It means that human sciences are required to carry direct driver behaviour analysis, as a complementary but really key component.

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