A new road safety indicator based on vehicle trajectory analysis

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Abstract

In 2014, in France, accidents on rural roads accounted for roughly 63% of road mortality (ONISR, 2014). Yet, the locations of accidents are increasingly spread, and it is becoming difficult for road managers to set priorities for interventions on their road network. They can no longer base their strategy on accident analysis. Road managers need to quickly measure the effectiveness of a modified facility, improvement of facilities or modification of the environment. On this type of site accident analysis requires a period of 3 to 5 years to determine the effectiveness of a change. This period of time does not meet the requirements of road managers or road users. To provide a high safety level, managers are implementing innovative developments: wall effect chicane at crossroads, dynamic warning signs, rural roundabouts, etc. Managers want to quickly assess these innovations. In addition, they have less and less money, so it is necessary to give them tools to help prioritize their intervention. It is also preferable for road managers to take preventive action rather than having to wait for accidents or serious injuries to occur, in order to carry out diagnosis and propose countermeasures. In this article, we propose a new safety indicator based on trajectory analysis. By trajectory, we mean a time-function that describes vehicle movement including not only its path on the road but also speeds and accelerations in both horizontal directions (longitudinal and transverse). These trajectories describe vehicle/infrastructure/driver interactions and reveal inadequacies that can lead to accidents. These trajectories are obtained using two roadside observation systems that analyse vehicle trajectories on two specific locations: curves and intersections on rural roads. The first tool is a local trajectory measurement system. It records trajectories of all vehicles passing through a specific zone. The goal is to observe abnormal paths that reveal dysfunctions in the vehicle/Infrastructure/driver system. The main applications-related contribution of this work focuses on developing a comprehensive solution for accurately estimating vehicle trajectories based on a combination of video images and range finder (telemeter) measurements. The purpose of the second tool

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is to improve understanding of dysfunctions at a crossroads and to evaluate the effectiveness of facilities. A precise study of patterns encountered on accident-prone intersections on rural roads showed that some situations are much more dangerous and frequent than others. In particular, most accidents at intersections are caused by vehicles crossing main roads. The second system presented in this paper detects and records conflicts between users on the secondary road who are crossing the main road, and users driving straight ahead on the main road. This kind of conflict represents the main type of accidents called crossing at grade accidents. The proposed risk indicator is equal to the number of conflicts (near-misses), weighted by the severity of the conflicts recorded in a given period. We chose to take the number of conflicts per hour. The purpose of these tools is to understand anomalies in the vehicle/infrastructure/driver system, and to evaluate the effectiveness of countermeasures on safety. Associated with risk indicators they make it possible to objectively assess driver behaviours with respect to the road infrastructure.

Keywords: trajectories; safety; evaluation; intersections; curves

1. Introduction and context

Accident statistics alone are of very little use to support research aiming to further reduce mortality and injuries, because of the low numbers of people killed per km/passenger or by km of road, especially in developed countries where the most obvious causes of accidents have already been eliminated, and because of the complex and multiple causes of any accident. Therefore, since 10 years, Ifsttar and Cerema carried out research into vehicle trajectory modelling and measurement, and “near-miss” identification, as well as increased road risk indicators, inappropriate driving behaviours with respect to environmental and infrastructure conditions, and risk-prone zones of the infrastructure (Goyat, 2007, Subirats, 2010).

The main idea is to develop a new concept of a vehicle’s “extended trajectory”, which is not limited to the vehicle path on the road, but comprises the vehicle's 3D location, speed, acceleration and sudden change in acceleration if needed, as a function of time, or the vehicle coordinates and its time derivatives up to the second or third order (Jacob, 2011). Detailed deterministic and probabilistic models of such trajectories are developed and implemented, to analyse and accurately link the output of the vehicle-driver-infrastructure interaction, i.e. the trajectory, with 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 scenarios. Severe or effective accidents are taken into account in this safety assessment, as well as frequent unsafe situations, as a risk indicator. E.g. a wheel encroaching on an emergency lane, an adjacent lane or a hard shoulder, is called a “quasi-accident”, or “near-miss”, and reveals a partial loss of control of the vehicle by its driver, and therefore inappropriate speed or actions with respect to the road and vehicle performances and environmental conditions. Such events are not rare, and therefore produce meaningful statistics, allowing forecasting and prevention of more severe failures, i.e. accidents. These tools and methods make it possible to change from corrective treatment of road safety problems, e.g. black spot mitigation after an accumulation of fatalities and injuries, to a series of preventive measures, such as driver warnings, self explaining roads, dynamic road information, advanced driving assistance systems (ADAS), etc. These measures can be evaluated by analysing their impact on the number of near misses, or on the probability of failure with respect to such a failure mode.

Then trajectory observatories are intended to provide, process and store objective and extensive measurements and data relating to vehicle (extended) trajectories. Analysis of these trajectories can lead to development of indicators of dangerousness of road infrastructure use. Several research projects have used this approach for bends, intersections, and low volume roads; such as the PREDIT 3 SARI programm, and its related projects RADARR, VIZIR, IRCAD, etc. (Jacob, Gallenne, 2010).
2. Trajectory definition

The hardware and software tools to collect, process and analyse the data described in sections 3 and 4 are called “Trajectory Observatories”, and by extension are the databases of recorded trajectories. Depending on the application and on the resources available, various measuring tools can be used. In most cases, several types of measuring devices must be combined to observe trajectories, according to vehicle type and traffic conditions. Personal cars and heavy goods vehicles behave differently, and therefore generate rather different trajectories. A vehicle can be “isolated”, “free”, belong to a “platooning”, or be constrained by other vehicles, according to the definitions in the Glossary of Terms (Olivero, Jacob, 2006). To analyse a vehicle trajectory it is necessary to know the boundary conditions applying to this vehicle, i.e. the trajectories of the preceding vehicles, and the environment parameters, which may be recorded by a video camera.

Four categories of trajectory observatories were defined (Table 1), depending on the location of the measuring equipment (on-board 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 roadside devices provide external measurements. Both systems are complementary:

- MITL/MITG: instrumented dedicated vehicles which generally deliver very detailed data (resolution, accuracy) for a limited number of trajectories and 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>
<thead>
<tr>
<th>Internal (on-board) means</th>
<th>External (roadside) means</th>
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<tbody>
<tr>
<td>“Local Trajectories” on limited spots &lt; 100 m (MITL)</td>
<td>(1) Internal Measurement of Local Trajectories</td>
</tr>
<tr>
<td>“Global Trajectories” on itineraries &gt; 100 m (MITG)</td>
<td>(2) External Measurement of Local Trajectories (METL)</td>
</tr>
<tr>
<td>“Reference Trajectory”</td>
<td>(3) Internal Measurement of Global Trajectories</td>
</tr>
<tr>
<td></td>
<td>(4) External Measurement of Global Trajectories (METG)</td>
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</table>

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

(i) **Microscopic traffic analysis 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 time between vehicles.

They 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 in class (2) or class (4) of observatories, according to Table 1.

(ii) **Local trajectory measurement systems**: are dedicated to black spot studies, e.g. a dangerous curves. They are designed to record, as accurately as possible, the full trajectories of all passing vehicles, in order to detect abnormal behaviours, revealing a dysfunction of the road-vehicle-driver system. This information is valuable for the road manager to understand the hazard risk of the black spot and evaluate the benefit of modifying the infrastructure. The risk index allows comparisons between different intersections or black spots.

(iii) **Traffic conflict detection systems**: are designed for a specific application, i.e. to detect local conflict situations between vehicles, generally at intersections (Amundson, 1977). They provide information such as:
3. Risk analysis in interurban curves

The aim of this work is to propose a measurement system to improve understanding of the relations between drivers’ behaviour and infrastructure characteristics on rural curves.

Some optical systems determine trajectory measurements, with the aim of detecting incidents to improve the reliability of measurements on a road zone (average) rather than at a local point. However, none of these systems fulfil the technical specifications, in particular in terms of measurement accuracy.

So we decided to develop a new measuring instrument called a “Trajectory Observatory”, combining two sensors which allow wide field measurement: the camera and the laser.

There are many fields of application for metrology of vehicle trajectories, in the road safety domain, in particular the study of dangerous bends. One of the recently identified possible uses for this type of system is observation of trajectories in order to develop a road user warning system in a blackspot. This section presents a tool that uses a calibrated trajectory observation system on real sites, to estimate vehicle positions and speeds. It continuously records the information produced by three cameras and a laser distance-finder.

3.1. Tool principle

From a survey of current roadside systems and existing methods, it is apparent that many systems are commercialised for only traffic measurement. Some optical systems also make it possible to measure trajectories, with the aim of not only detecting incidents but also improving measurement reliability by examining one (average) zone rather than a single point. A decision was therefore taken to produce a new measurement tool in its entirety (hardware and software) called a Trajectory Observatory (ODT for Observatoire de Trajectoires in French), combining the two commercially available sensors that enable “wide field” measurement: the camera and the laser. Development of a video system is therefore justified by the domain of application that it covers, i.e. with strong constraints and precision requirements: measurement of vehicle trajectories on curves. The functional requirements of such a system have been identified by a group of road safety experts, and the performance levels are summarised in Table 2:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal position</td>
<td>5 m</td>
</tr>
<tr>
<td>Longitudinal speed (dX/dt)</td>
<td>5 km/h</td>
</tr>
<tr>
<td>Transverse position (Y)</td>
<td>20 cm</td>
</tr>
</tbody>
</table>

Since the most thoroughly explored scientific domain was object tracking, a bibliography was drawn up to identify the most appropriate methods for our problem. The choice was made to select probabilistic methods and the “Markov Chain Monte Carlo” (MCMC).

The main reason for this choice was that it enabled development of two operational methods for precise estimations of vehicle trajectories, based on a combination of video images and distance-finder measurements. These tracking methods are based on a new background/shape subtraction method, the combination of a kinematics model and an observation model, and finally on an original technique for sensor merging, using a particle filter re-sampling process. The advantage of the first “sequential” method is the capacity to estimate all light vehicle trajectories. This enables it to retrieve a large quantity of information (5 parameters per measured point), in proportion to the time spent analysing it. The second “global” method allows for more responsiveness and more detailed analysis, thanks to a considerable reduction in the tracking parameters. However its disadvantage is that it
cannot track “atypical” trajectories. However this characteristic can be used as a criterion for classifying trajectories. Finally the different steps in these methods were validated using numerous master trajectories. These master trajectories were tracked and measured by a vehicle equipped with a GPS providing precision to the nearest cm, at different speeds. The two methods were then compared to each other, and to these same situations in the field.

Fig. 1. For the calibration, each beacon, visible in the image, is cut by the laser plan of the rangefinder.

3.2. Applications

In a few cases, “loss of trajectory” will be brought about at least partially by the infrastructure, either because the road layout causes drivers to behave in a dangerous and inappropriate manner, or because even in a case of normal driving at the recommended speed for the route, the trajectory causes the vehicles – or some of them – to reach the limits of control capacity. In this case, in principle the relevant zone will be characterised by a recurrence of analogous accidents. In such a case, the road manager can and must intervene on the infrastructure to make it safer. Sections known to cause accidents are often curves that are poorly designed, crossroads, roundabouts, or zones of traffic exchange between very large and very busy roads. The vehicles involved in accidents may be light vehicles, heavy goods vehicles or two-wheel vehicles. On a section that is effectively accident-prone, the most effective intervention will be designed by analysing in detail not only the accidents that have occurred, but also the near-misses, i.e. situations in which a vehicle was almost involved in an accident but was able to avoid it in extremis and subsequently continued on its journey. The difficulty arising when analysing these situations is that they are not observed. The consequences of an accident are observed, but we are unaware that the near-misses even exist.

Development of Trajectory Observatories (ODT) aims to solve this problem.

In the remainder of this article, we describe how an ODT was installed on a dangerous curve in France.

The aim of this operation was to analyse driver behaviour, in order to better understand the causes of accidents on bends. Instruments were installed on the curve according to the measurements necessary to analyse driver
behaviour. The systems measuring vehicle positions were installed in the middle of the curve, defined as the point with the smallest radius. Since electro-magnetic loops only measure speed, they were placed ahead of the curve (approach speed) and at the points of maximum acceleration and deceleration. Radar units were used in addition to other systems for speed measurement.

Three main groups of data can be analysed as a function of time, using “roadside” measurement systems: traffic, speed and lateral position of the vehicles. By analysing speed through the entire bend, it is possible to verify not only that the statutory speed is “consistent” with the effective vehicle speed, but also that the design of the bend does not cause a dangerous sudden change in the speed profile. In addition, the traffic data warns the manager if design rules are no longer appropriate for current traffic. This analysis verifies that drivers are using the road in the manner for which it was designed, and are not putting themselves in an “abnormal” situation. Here, the vast majority of drivers, seeing that no vehicles are approaching on the other side of the road, decide to take the shortest path and cut across the continuous line. To illustrate this, the following series of images show two of the categories of positions adopted:

![Fig. 2. Example of vehicle position.](image)

The analysis of the speed all along the curve allows checking whether the legal speed is “coherent” with the reality and also if there isn’t some ruptures in the signal related to a road design problem. The traffic profiles also condition the design of the road and verify that the conception rules are still sufficient.

This analysis checks that the drivers use the road according to its design and that they do not reach abnormal situation. Here, the large majority of the drivers, not seeing vehicle on the other way, decides to take the shortest way and thus to cut the continue line.

This tool was used as a database for probabilistic analysis of trajectories to identify families at risk (Koita, 2011).

4. Risk analysis at interurban junctions

On interurban roads accidents at junctions are a major road safety hazard. They represent 1% of journey distance but 12% of reported fatal or serious accidents. Furthermore, their number has been on the increase since 2005, passing from 9% in 2005 to 12% in 2012. The analysis of accident reports shows that the main type of accident is a side impact collision, and that the people over 60s are likely to be involved.

Specific difficulties make it hard to analyse accidents. Firstly, the accident reports provide little information concerning the cause of the accident. In many instances the accident involves a vehicle coming from a secondary road, where the driver didn't see the vehicle on the main road and pulled out. The statement of the driver of the
vehicle coming from the secondary road is rarely taken, due to the seriousness of their injuries. Secondly, personal injury accidents occurring at a road junction are particularly rare. Therefore, any meaningful analysis must be made over a long period of time, from 3 to 5 years.

The situation with road safety at junctions has led road transport authorities to demand that they be given adequate tools and methods to diagnose, evaluate and grade the problems involved. In order to make better use of resources, they also want the tools to define the risks involved. Furthermore, it is important to understand why a traffic junction does not work as intended, without waiting for accidents to happen. Counter measures can then be put in place and improvement works undertaken. It is, however, essential to have indicators in place both before and after such corrective actions and infrastructure modifications, for evaluation purposes. Response times must be quicker than simply analysing the circumstances of personal injury accidents.

Given the context and needs involved, procuring and analysing data concerning incidents at road junctions is not only pertinent but also complementary to the study of personal injury accidents.

4.1. Tool principle

The aim of the system for analysing risks at road intersections is to explain why the junction is not working properly. It comprises the necessary equipment to collect the data and a method for analysing the data. The equipment detects and records incidents between a vehicle coming from a secondary road pulling out in front of a vehicle having the right of way on the main road and travelling straight ahead. The equipment can easily be installed at the side of the road in half a day, without interfering with traffic flow.

As soon as a vehicle (green) on the secondary road moves off and into the intersection, two incident time intervals are calculated: the incident time interval on the first axis and the incident time interval on the second axis. If a vehicle is detected on the main road during these time intervals, a side-on collision will take place. The time to collision between a vehicle on a main road and a vehicle coming from a secondary road is defined as the difference between the instant when the vehicle moving off from the secondary road is detected, and the instant a vehicle on the main road is detected during one of these intervals.

A risk index is calculated using the recordings of the detection of the vehicles on the secondary and main roads and their speeds. Research into side impact collisions is based on calculation of the time to collision. The risk index of a road intersection is equal to the number of incidents which occurred, with a weighting based on the seriousness of the incident recorded. The index is calculated over a given period of time and re-calculated to give a daily (24 hour) risk index figure. Thus, the risk index is defined as follows:

\[ I_r = \sum_i G_i(C_i) \]  

where:
\( I_r \) is the risk index, \( C_i \) is the conflict number \( i \) and \( G_i \) is the severity of conflict number \( i \)
And $G_i$ is defined as followed:

$$G_i = k \frac{v^2}{T}$$  \hspace{1cm} (2)

where:

- $v$ is the user speed on the priority road,
- $T$ time between both vehicles at the conflict point,
- $k$ is a constant calculated such that if the accident is inevitable then $G$ is close to or greater than 1.

$G$ is a function of the square of the speed, since the braking distance and impact severity are a function in particular of the square of the speed.

This risk index makes it possible:

- to compare several crossroads or several types of crossroads. For example, on an itinerary, the most dangerous crossroads will be those with the highest risk indices;
- to estimate the foreseeable number of accidents on a crossroads. This estimate can be calculated after establishing the correlation of the number of accidents as a function of the risk index, following deployment of the system on several sites;
- to measure the effect of intervention on the infrastructure by comparing before and after the works. For example, if the index for a crossroads is divided by 2 after intervention on the infrastructure, its level of risk would be improved by 50%.

### 4.2. Tool description

As the system must be implemented on busy roads, it has to satisfy some constraints.

- it must be possible to set up the entire system on different types of rural road intersections. It must be easy to install, and also easy to dismantle,
- the system must use an autonomous energy source such as solar or wind power. One week of measurement is enough to have an idea of the intersection's safety,
- the system must comply with regulations in force concerning road user safety and roadside obstacles,
- we must ensure the system is protected against deterioration (theft, atmospheric conditions, etc…).

The developed system detects vehicles driving on the main roads. We chose to use speed radar, from among existing traffic sensors. The speed parameter makes it possible to distinguish vehicles travelling in a straight line from vehicles turning leftwards that cannot be involved in a quasi-accident.

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Fig. 5. System illustration.
4.3. Example of application

The system was installed on the RD90/RD3 intersection in the municipality of Houppeville in the general council Seine-Maritime following a fatal accident that occurred on 2 June 2011.

![Image of the intersection](image)

**Table 3. Conflicts analysis before and after works laying out.**

<table>
<thead>
<tr>
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<th>Before works</th>
<th>After</th>
</tr>
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<tbody>
<tr>
<td>Number of conflicts</td>
<td>61</td>
<td>40</td>
</tr>
<tr>
<td>Average severity</td>
<td>0.25</td>
<td>0.23</td>
</tr>
<tr>
<td>Risk index (I_r)</td>
<td>5.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>

We note that the number of conflicts dropped sharply on the secondary road carrying the most traffic. The risk index on the intersection was virtually halved. On the other branch, we do not note any marked improvement, due in particular to the visibility conditions which are and remain poor in this first phase of the works. The average speed of users involved in crossing at grade conflicts is greater than the average speed of all users of the main road. Overall, the average severity on this intersection has remained constant, despite the reduction in speeds on the main road, but with shorter collision time.

5. Conclusion

In this paper, we present the concept of trajectory observatories developed along the last decade by the IFSTTAR and Cerema. It provides 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. These roadside tools can monitor all the vehicles over 100 m in length zones.

These devices are useful for road managers to diagnose, evaluate and grade the problems involved. They allow managers to know what happen on their road without waiting accidents to occur.

Today it is necessary to finalize the development of these tools to conduct industrial transfer.

References


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