VIENNA 2018 TRA
TRANSPORT RESEARCH ARENA
A digital era for transport
solutions for society, economy and environment

Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Kinematics of powered two-wheelers at bends on intercity roads

Alexandre Hublart, Peggy Subirats, Olivier Floris*

CEREMA Normandie Centre, Grand Quevilly 76120, FRANCE

Abstract

In France, powered two-wheelers (PTWs) account for 18% of fatal accidents, and PTW riders are 27 times more likely to be killed than car drivers. More than one-third (40%) of these fatal accidents occur at bends on intercity roads. Based on this observation, a prototype vehicle embodying the full range of intrinsic and extrinsic parameters was developed in order to analyse rider behaviour. The Rider Behaviour Analysis Motorcycle (*Moto d'Analyse du Comportement du Conducteur*, MACC) was used to analyse speed and lateral acceleration, capture videos and measure vehicle dynamics and trajectories. The findings revealed certain practices that had never previously been quantified. Alongside this behavioural study, we will also highlight some key accident research statistics associated with PTWs at bends on intercity roads.

Keywords: powered two-wheelers, bends, intercity roads, speed, trajectory, dynamics.

* Corresponding author. Tel.: +33-235-688-135; fax: +33-254-554-871.
E-mail address: {alexandre.hublart;peggy.subirats;olivier.floris}@cerema.fr

For almost 10 years now, Cerema (Center for Studies and Expertise on Risks, Environnement, Mobility and Development) has been studying the mechanisms that drive road user behaviour in potentially hazardous conditions of all types. This theme has already been covered several times, but only a handful of studies have produced qualitative and quantitative data specific to PTWs. However, the use of an on-board system to record comprehensive information as the vehicle crosses an element of infrastructure (such as inertia, speed and handlebar controls, and a camera to film the surrounding environment) marks a new addition to efforts to detect PTW behaviour. Some 40% of fatal PTW accidents occur at bends on intercity roads. Of these, 85% involve heavy motorcycles (over 125 cc). Based on this observation, we decided to focus this study on PTW behaviour at bends on intercity roads, following prior analysis of such behaviour on approach to roundabouts and chicanes/pinch points.

1. PTWs and bends: state of the art

1.1. PTWs in France: usage and risks on the increase

In France, over nearly 15 years, the sale of PTWs has greatly increased (*Fig. 1*). Between 1994 and 2013, the number of PTWs rose from 2,352,000 to 4,100,000 (an increase of over 40%). PTW traffic is estimated at about 2% of total traffic. In 2016, PTWs accounted for almost 28% of fatal accidents. Based on the ratio between distance travelled (in km), vehicle categories on the road and number of fatalities per accident, these figures – produced by the National Interministerial Observatory for Road Safety (ONISR) – also reveal a fatality risk for car drivers of 3.5 deaths per billion km travelled. Among PTW riders, however, this risk is 27 times greater (96.4 on all road types, 92 on urban roads, 116 on non-urban roads, and 39 on motorways).

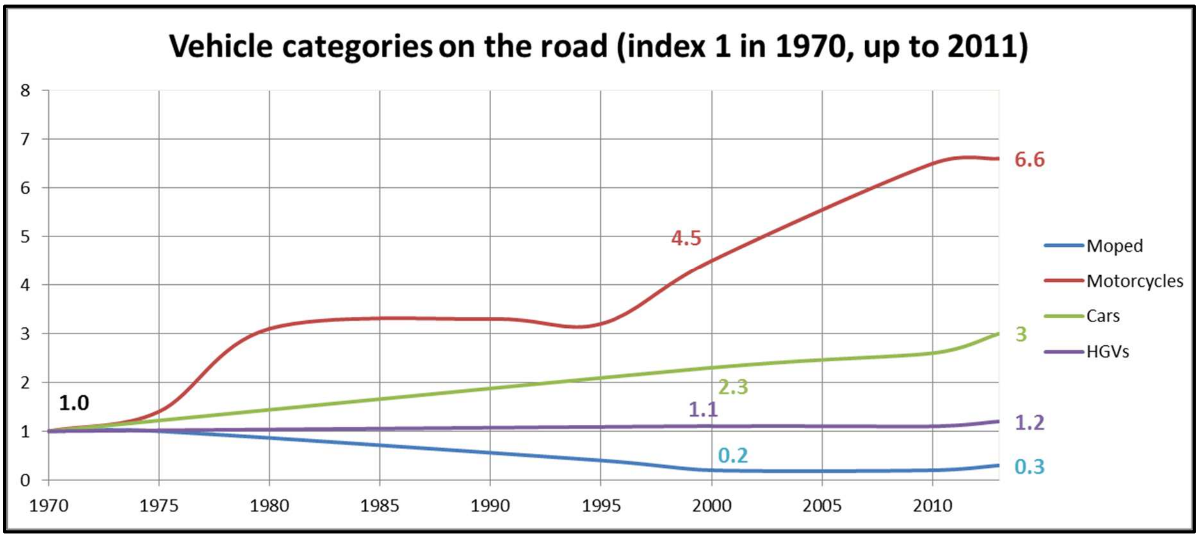

Fig. 1. Changes in vehicle categories on the road

These figures reflect both the attractiveness of PTWs for the French people, and the scale of the risk involved when travelling on this type of vehicle. These two factors point to the need for acquiring more knowledge, particularly about behaviour, in order to suggest action to reduce the number of fatalities on the road. For this reason, in 2010, PTW safety became a “political priority” in France in terms of road safety. Historically, car drivers have been seen as the most important category to target in order to reduce the number of road fatalities.

While various actions have successfully reduced fatality rates on French roads, the figures show a much smaller reduction among PTW riders than car drivers (-35.2% compared with -66.4% between 2000 and 2015). In 2015, motorcyclists accounted for 19.8% of road deaths in France *(Fig. 2)*, placing the country third on the list of the most dangerous European countries for PTW riders.

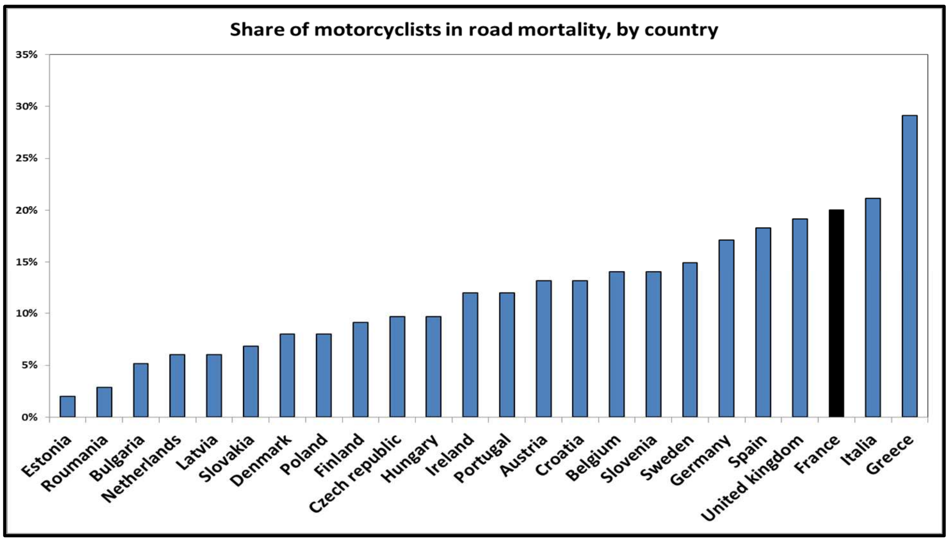

Fig. 2. France's poor record by European standards

Work carried out by the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) and published in the report on road safety potential in 2008 shows via a public health approach that, since 2004, seriously injured PTW accident victims with persistent after-effects (*NISS9+*[†]) have become greater in number than those injured in cars. Few studies looking at the relationship between PTW accidents and infrastructure. Cossalter et al. (2002, 2015) and Slimi et al. (2009, 2015) have developed a model to simulate PTW dynamics, but there has thus far been no study focusing specifically on PTW behaviour at infrastructure.

1.2. PTWs and bends on intercity roads: a poorly understood subject

The ONISR report that among the PTW riders who were killed, 40% are killed inside curves in 2015. Of these fatal accidents, 85% involved heavy motorcycles (over 125 cc). Several observations can be extracted from the accident analysis:

- Road maintenance issues (potholes, gravel, presence of gas oil, etc.) are at fault in less than 2% of cases.
- Accidents in which a PTW rider is at fault occur in equal proportions on right-hand and left-hand bends.
- Accident severity is higher on left-hand bends, which may be due to the fact that more obstacles are encountered on bends in this direction.

The evidence clearly shows that more PTW accidents occur at bends than on any other type of infrastructure, although the most recent research into accident-causing factors at bends on French roads dates back to 1992. The document reveals that, on rural main roads, the two types of bend where accidents occur most frequently are as follows:

- isolated, small-radius (less than 150 m) bends on easy sections of road;
- moderate-radius bends (less than 250 m) with design flaws (irregular curvature of the bend, for example).

Sub-standard verges make it difficult for PTW riders to correct their trajectory if they stray slightly off course; aggressive obstacles along the edges of bends (and especially on the outside of the bend) can seriously exacerbate physical injuries if the PTW leaves the carriageway; and sight distances on bends are 3 seconds at most (slightly less than on a winding road), which makes it more likely that accidents will occur. The document also reveals that curvature and verges are the key variables that make bends accident hot spots, with analysis showing that surface characteristics almost always interact with other accident-causing defects and are rarely one of the initial causes of an accident on their own.

The French Office of Technical Research into Roads and Motorways (SETRA) published a practical guide on bend signs and marking in 2002, setting out the five main factors that lead to PTW accidents at bends:

- the difference between approach speed and speed around the bend;
- the tightness of the bend;
- the readability of the bend;
- the visibility of the bend;

[†] New Injury Severity Score

- the length of the bend.

Of 6,448 single PTW accidents studied by Majka et al. (2007), 57% took place on a curve, compared with 43% in a straight line, mainly on wet roads in both situations. According to Berg et al. (2005), PTW accidents occur more on left-hand curves than on right-hand curves. On the other hand, the turns are often equipped with safety slides, particularly the difficult curves which represent a danger for the road users. However, PTW riders shocks against this type of obstacle lead to a high risk of serious injury and mortality. Moreover, the turns are often equipped with safety slides, particularly the difficult curves which represent a danger for the road users. However, PTW shocks against this type of obstacle lead to a high risk of serious injury and mortality (Ouelett (1982); Laumon (2002); Miquel (2002); Gabler (2007))

Moreover, Cerema found that left-hand curves are apparently more difficult to negotiate than right-hand curves (subjective data), and divided curves into four zones:
- Approach zone: PTW riders assess the difficulty of the curve and adjust their speed accordingly.
- Discovery zone: PTW riders remain in the central axis but look ahead to determine where the apex lies.
- Turning zone: PTW riders approach the apex and are at their most vulnerable.
- Re-acceleration zone: PTW riders return to the right position on the road.

Spacek (2005) pointed to six trajectory patterns within these zones: cutting, ideal, swinging, drifting, correcting and normal. These trajectories are described in detail later in this document.

It was not possible to quantify the information mentioned above because of a lack of tools to determine the distribution of motorcyclists across different trajectory patterns and the speeds at which PTW riders approach, negotiate and exit curves. It is for this reason that Cerema started on the MACC project.

2. Tools and methodology

2.1. Presentation of the MACC

The division, which has almost 30 years' experience in car instrumentation, drew on past work to produce a technical architecture drawing. The drawing is based on the same principle as the very first instrumented vehicle, but on a PTW. This new tool was developed with several objectives in mind:
- to gain a deeper understanding of the environment surrounding the PTW (cameras);
- to learn about PTW dynamics (Inertial Measurement Unit, or IMU);
- to measure trajectory and speed on a continuous basis (GPS);
- to monitor handlebar controls (data acquisition board).

During the selection phase, we sought to identify the most popular motorcycle in France (in 2008) in terms of sales. Our research indicated that the Suzuki GSF650 Bandit S was one of the top 10 best-selling PTWs in 2007.

Fig. 3. The MACC

2.1.1. Inertial Measurement Unit

The IMU indicates the angular position of the motorcycle, providing information such as roll, pitch and yaw, as well as acceleration in all three axes.

For this purpose, we focused on a specific type of IMU: the Attitude and Heading Reference System (AHRS), using MicroElectroMechanical System (MEMS) sensors. This type of IMU is capable of measuring movements in real time and calculating the orientation of an object at extremely high frequency (up to 100 Hz).

In order to use this IMU effectively, we had to determine the centre of gravity of the PTW. We found that the motorcycle's fuel tank was the centre of gravity.

2.1.2. Handlebar controls

When studying the wiring diagram of the selected PTW, we sought to identify the relevant controls that could be recorded using a data acquisition board. We identified two types of data that could be captured: "digital" data from the brakes (front and rear combined), lights (indicators and dipped beams) and clutch lever; and "analogue" data from the throttle (in %) and gear changes (from 1 to 6 for the GSF650). All of these data are managed by a 100 Hz data acquisition board.

2.1.3. GPS

A GPS system allows continuous (rather than occasional) data to be collected. By cross-referencing data from this GPS receiver with the above-mentioned sensor data, we will be able to analyze rider behaviour at a specific point and over an unlimited distance. The frequency of this receiver is different from the other sensors, since we take position readings at 18 Hz.

2.1.4. Cameras

A camera is an essential component of our prototype, since it provides a visual image that can be cross-referenced with the data acquired, to give us an understanding of the PTW's behaviour in relation to its surrounding environment. For this reason, we installed two cameras. The first films the environment around the PTW *(Fig. 4a)*, and the second records the position of the front wheel on the road or (depending on orientation) the rider's head movements *(Fig. 4b)*.

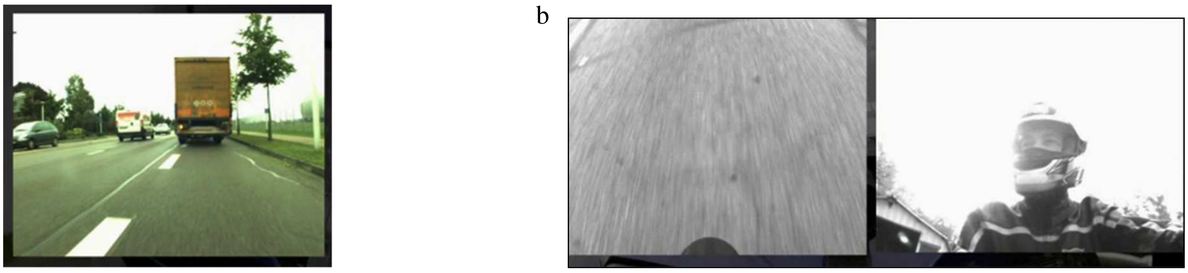

Fig. 4. (a) View of the environment camera (b) View of the road/helmet camera

All of these measurements are managed centrally by a laptop PC, to ensure perfect synchronisation between the data and images.

2.2 Experimental protocol

The study focused on a panel of 18 motorcyclists. All of the participants were CEREMA Normandie-Centre personnel, with the panel made up exclusively of men (no women were available to take part), each covering an average of around 3,000 km per year on a motorcycle. The riders were unaware of the purpose of the experiment and the only instruction they received was to drive naturally. Each rider travelled along the route once during off-peak times in order to limit disturbance from traffic and to have as many "free" PTWs as possible[‡].

The route between Rouen and Gournay-en-Bray in Normandy was chosen because it comprised a high number of bends on intercity roads (30 bends in each direction, i.e. 60 bends in total). Each bend was categorised using a method based on the difference between bend negotiation speeds (1) and approach speeds (2). The speeds were calculated from data extracted from MOGEO®, a device used by the Ministry for the Ecological and Inclusive Transition's scientific and technical network. The device measures slope (*Pe*), straight line (*Aldroit*), distance from the urban area behind the bend (in metres) (*Distagglo*) and bend radii (*R*) on a route in the flow of traffic.

$$V_d = 102/(1+346/R^{1.5}) \tag{1}$$

[‡] A vehicle is free if its trajectory is not correlated with those of any of the vehicles in front of it. A vehicle is free when it can reach its desired speed.

$$V_a = \left[V_{d-1}^2 + 2\times(0.8 - g \times Pe/100)\times(\min[Aldroit, Distagglo] - 75)\right]^{1/2} \quad (2)$$

g: acceleration due to gravity, i.e. 9.8 m/s²

The smaller the difference between speeds on the bend and on approach, the less hazardous the bend. For category A bends, the difference (V_a-V_d) is less than 8 km/h. Category B bends have a difference between 8 and 16 km/h, category C bends between 16 and 40 km/h, and category D bends have a difference in excess of 40 km/h.

We then categorised the bends according to radius:
- Small radius: < 150 m
- Moderate radius: 150 m < R < 250 m
- Large radius: > 250 m

A road safety expert inspected each bend to observe horizontal and vertical signs and marking and the nature of the verges.

Once all of the motorcyclists had travelled along the route, we collected the data and carried out three consecutive processing operations. First, we filtered the data to include “free” motorcyclists only (using camera footage). Next, we discarded all but the 90 km/h bends for consistency purposes, leaving 25 of the original 60 bends. Finally, we broke down each bend into three sections: entrance, middle and exit. Since each bend had different geometry, we completed the breakdown process using the zone types mentioned previously.

Once this stage was complete, we analysed PTW rider behaviour by looking at the following parameters:
- roll (IMU data);
- speed (GPS data);
- trajectory (combined GPS data and video footage).

3. Speed, roll and trajectory: how direction affects kinematics

3.1. Speeds according to radius and curve direction

Initially, we observed the dispersion of speeds on the bends included in the study (i.e. those limited to 90 km/h). We found no significant differences in the distribution of speeds between left-hand and right-hand bends. We obtained similar findings when looking at the bends in three sections (entrance, middle and exit), i.e. there was no significant difference according to direction. The data showed a median speed of 90 km/h, within a range of 60 to 120 km/h. Minimum speeds appeared to be lower on left-hand bends (between 40 and 60 km/h), than on right-hand bends (all above 60 km/h).

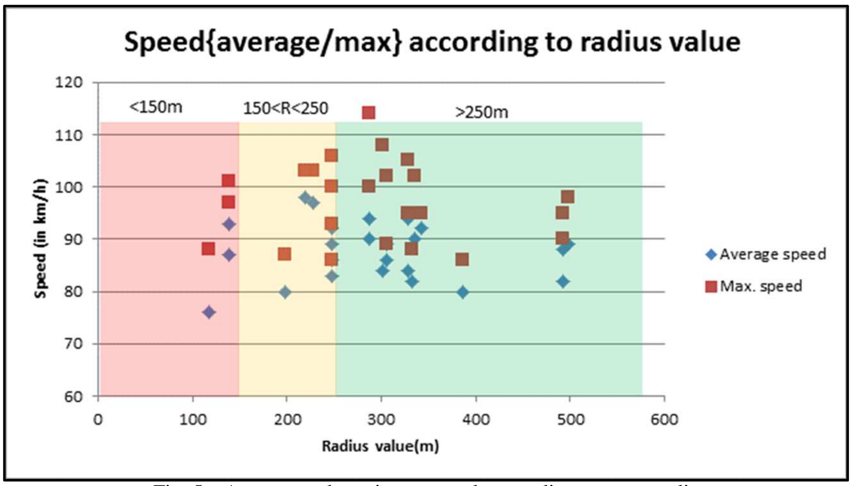

Fig. 5. Average and maximum speeds according to curve radius

Looking again at average speeds, we found no discernible trend according to curve radius. We would have expected to see speeds increase in line with radius (since larger-radius bends are easier for PTWs to negotiate), but the data showed consistent speeds of between 75 and 100 km/h across the board (*Fig. 5)*. However, we observed maximum speeds in excess of 100 km/h at bends with a curve radius between 150 and 350 m.

Finally, we looked at how speed changes around the bend (300 metres before and after the apex), according to bend type and direction (*Fig. 6*).

a b

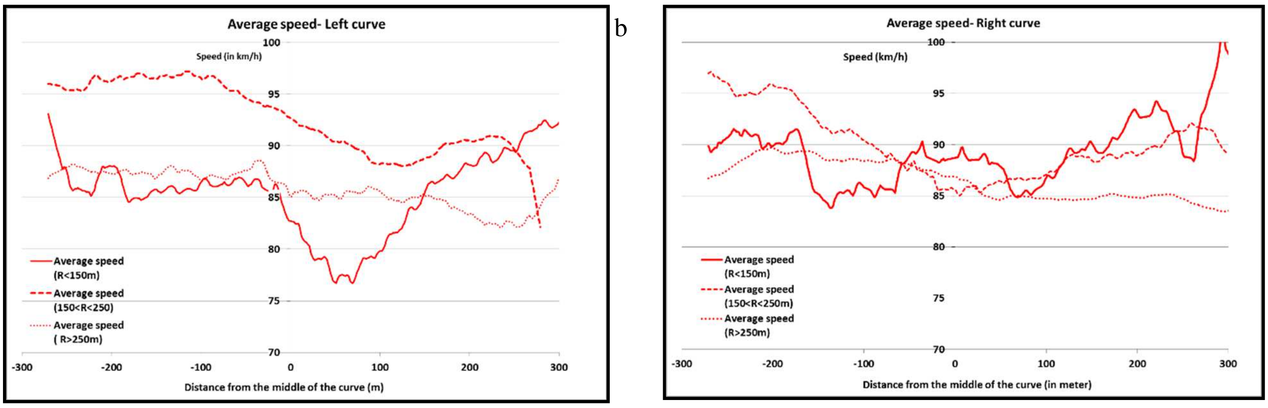

Fig. 6. Rolling average speeds on left-hand (a) and right-hand (b) bends

The graphs below show two different behavioural patterns, especially on small-radius bends. On left-hand bends, average speeds drop from 85 to 77 km/h, before returning to “cruising” speed 150 metres after the apex. However, the drop is much less significant on right-hand bends, with a speed reduction of barely 5 km/h (from 90 to 85 km/h). On large-radius bends, speeds remain relatively constant throughout (around 87 km/h on average). Finally, it is interesting to note that while the maximum speed limit is 90 km/h, riders only exceed this limit as they approach the apex of moderate-radius left-hand bends. On right-hand bends, they remain consistently below the limit.

Looking at “speed” alone, it is difficult to detect any particular trends. However, it appears that riders find it harder to negotiate tight bends that bear to the left than those that bear to the right (speed drop of 8 km/h on left-hand bends, compared with 3 km/h on right-hand bends). We analysed PTW roll to determine the reasons for this observation.

3.2. *Roll: proof that left-hand bends are harder to negotiate?*

We gathered roll data from the IMU fitted to the fuel tank. Figure 7 shows the roll data, in both directions, 300 metres before and after the entrance to the bend.

a b

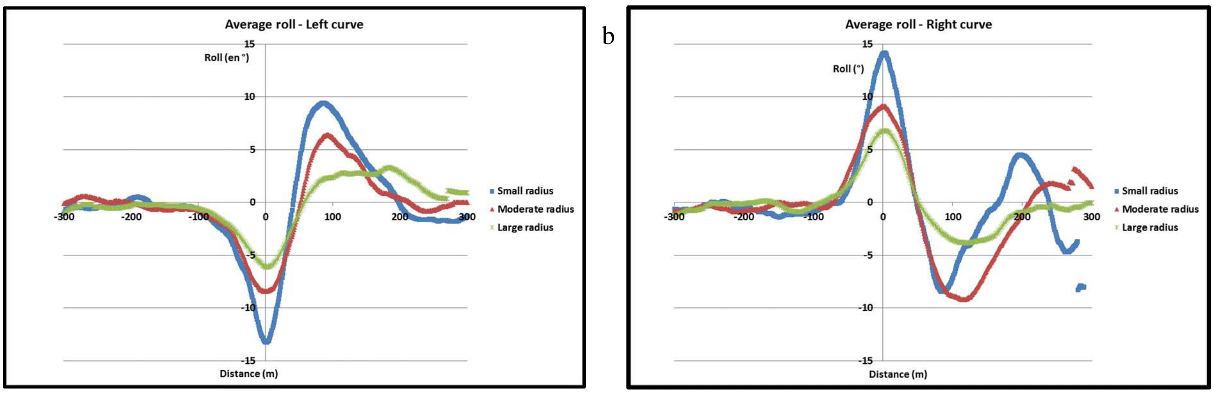

Fig. 7. Average roll according to right-hand (a) and left-hand (b) radius category

Roll amplitude is largely identical for all three categories of bend according to direction. The figures also show two distinct movements – the first between -100 m and 50 m, and the second between 50 m and 200 m. This means that PTW riders anticipate oscillation movements 100 m before they reach the apex of the bend. These two periods show how riders counter-balance their vehicle before returning to the vertical position. Irrespective of the bend direction, roll varies over a distance of around 300 m. The larger the radius, the lower the roll (around 5° on large-radius bends, compared with 15° on bends with a radius less than 250 m).

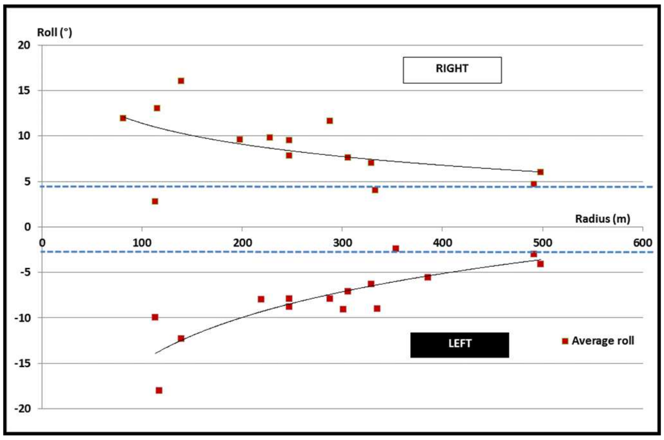

Fig. 8. Average roll at the apex according to precise radius value

Looking at each bend individually, we produced the following graph that supports our previous assertion that riders take less action to counter-balance their PTW on large-radius bends. This allows us to hypothesise that, on a bend, a PTW rider will always counter-balance the vehicle by at least 3° (absolute value), irrespective of the bend direction or type.

Finally, overlaying the graphs in figures 6 and 7 (speed and roll) reveals that average speed (especially on low-radius bends) falls when the rider takes counter-balancing action. This observation is particularly true on tight left-hand bends, which suggests that PTW riders find such bends harder to negotiate and therefore reduce their speed. On bends in the opposite direction, with the same amplitude values, the motorcycle's movement remains unchanged.

3.3. Trajectories around bends

The riders' trajectories were established using camera footage and GPS data. We then split the motorcycle's position into three categories (inside, centre and outside) at three points along the horizontal alignment of the curve (entrance, middle and exit). We then compared the data with Spacek's five standard profiles:

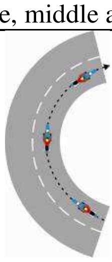	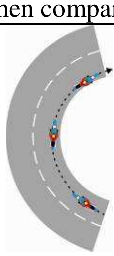	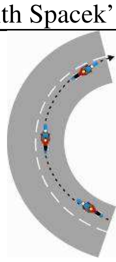	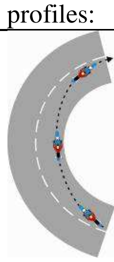	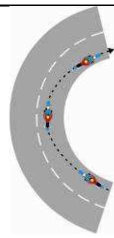
Ideal	Swinging	Drifting	Cutting	Correcting
Parallel with the radius, no off-path movement	Inward off-path movement in the middle of the curve and/or at the exit, no return	Outward off-path movement in the middle of the curve and/or at the exit, no return	Inward off-path movement in the middle of the curve, then outward at the exit	Outward off-path movement in the middle of the curve, then inward at the exit

Fig. 9. Trajectory type according to Spacek (2005)

In his study, Spacek also posits a sixth trajectory type, known as "normal", lying somewhere between "cutting" and "ideal", i.e. with slight inward movement in the middle of the curve then return to the original position. In light of the accuracy of the GPS system, we opted not to include this trajectory in our study. We recreated a total of 254 trajectories from camera footage and GPS data. The histogram below provides an overview of the distribution of trajectories according to curve direction:

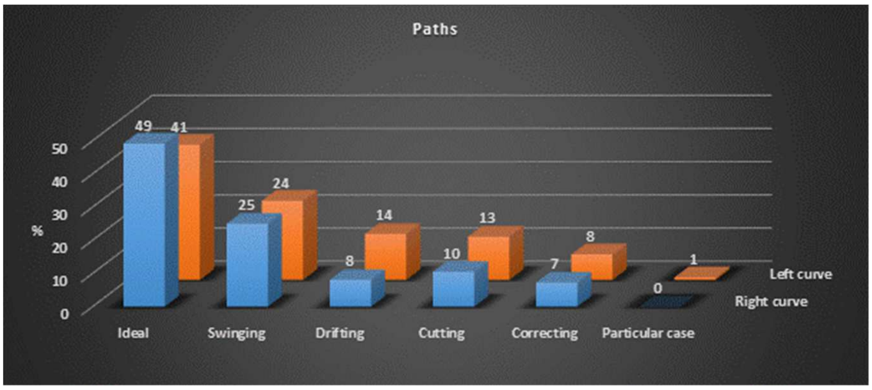

Fig. 10. Observed trajectories by curve type

The histogram above shows little difference between right-hand and left-hand curves, with around half of trajectories falling in the "ideal" category and in excess of one-third involving movement towards the inside of the bend (swinging and cutting). However, the figures do show that "drifting" trajectories are more common on left-hand bends than on right-hand bends (14% against 8%).

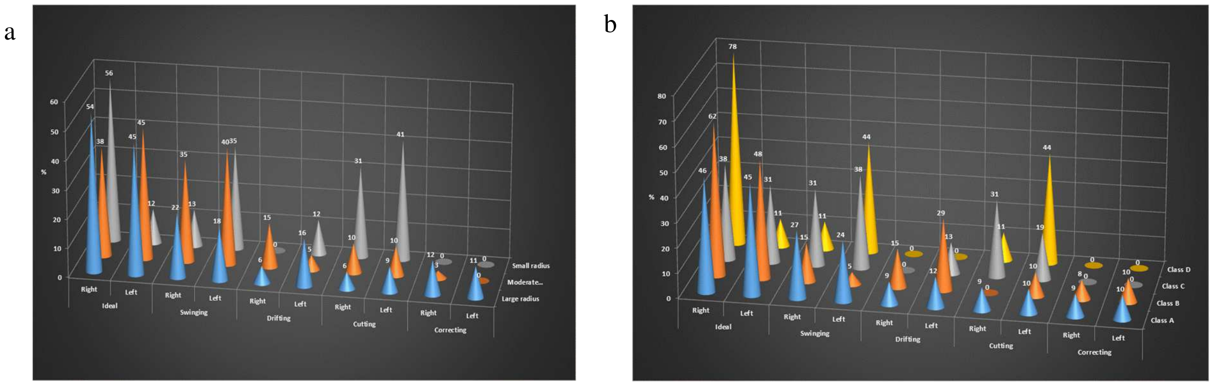

Fig. 11. Curve trajectory according to bend type (a) and bend category (b)

The two histograms above show how trajectories are distributed according to bend type and category, revealing that half of riders take "ideal" trajectories on large-radius curves, but showing no differences between left-hand and right-hand bends. The data also show that trajectory dispersion increases as bend radius decreases, and point to some differences between left-hand and right-hand bends:

- on right-hand bends, more than half of trajectories are "ideal";
- on small-radius curves, inward movement (swinging and cutting) occurs in 76% and 44% of trajectories on left-hand curves and right-hand curves respectively.

The roll figures in these two histograms are similar because they encompass the same results. However, it is interesting to see how the bends are grouped together. For example, the "large radius" and "category A" section has similar roll figures to the "small radius" and "category D" section. For moderate-radius bends, meanwhile, the categories are more mixed, primarily across categories B and C.

4. Conclusions and prospects

The MACC system was designed with numerous objectives in mind. The general aim was to create a non-intrusive data collection system in order to analyse PTW rider strategy, to learn about PTW practices under normal driving conditions, and to identify the behavioural and dynamic characteristics of the vehicle on open roads in order to improve PTW safety. Road design guides rarely consider PTW riders because there is insufficient qualitative and quantitative data. This study provides some of the missing elements, revealing how PTW speed and roll differ according to curve direction (right/left) and, to a greater degree, radius. Indeed, the study's findings show that low-radius left-hand bends appear to be the most difficult to negotiate. In terms of trajectories, the study compared bend types and categories and found that the formulae used to determine bend categories (based previously on the car database only) were consistent with results for PTWs and, therefore, that the formula can also apply to PTWs. However, this hypothesis will need to be tested with a statistical study.

In terms of prospects, there are several possible avenues for future research in the coming years. The study will continue in 2017/2018 since, during the experiment, Cerema also collected data using the Driver Behaviour Analysis Vehicle (*Véhicule d'Analyse du Comportement du Conducteur*, VACC) – an experimental car that formed the basis of the MACC and produced similar data – comparing speed, acceleration, trajectory and controls along the same predetermined route. Moreover, we would like to improve video recording and analysis capabilities, including path tracking and 3D modelling of PTW dynamics. We have already conducted initial tests in this area, using two omnidirectional cameras placed on both rear-view mirrors. Another potential avenue of exploration would be to fit the system to a fleet of PTWs, thereby extending the size of the panel and obtaining more data about PTW dynamics. The system will first need to be made lighter. One idea in this respect is to create a smartphone application that combines all the measurements included in the first version of the MACC, as well as images recorded by a sports camera fixed to the rider's helmet.

This increased sample size will enable us to analyse a new type of interaction, i.e. the interaction between rider and PTW. By considering the rider's psychological profile and data about his/her personal motorcycle, we will be able to analyse the behaviour of PTWs during emergency manoeuvres. For example, in terms of emergency braking, this would enable us to answer a number of questions. In what situations may braking be considered emergency braking? What technique does the PTW adopt during emergency braking? What effect does speed have on emergency braking distance? This new type of approach will provide quantitative/measured data for PTW behavioural studies, the majority of which have, until now, been based on subjective/non-measurable data.

5. References

Berg, F.A., Rucker, P. Gartner, M., Konig, J., Grzebieta, R., Zou, R., 2005, Motorcycle impacts into roadside barriers – Real-world accident studies, crash tests and simulations carried out in Germany and Australia. ESV: 19th international technical conference on the Enhanced Safety of Vehicles, June 6-9 2005, Washington, D.C. – USA. Paper N° 05-0095. http://www.nhtsa.dot.gov

Cossalter, V., Lot, R.,2002, A motorcycle multi-body model for real time simulations based on the natural coordinates approach., *Vehicle System Dynamics*, Vol. 37, No. 6, 2002, 423-447.

Cossalter,V., Doria, A., Massaro, M., Taraborrelli, T.,2015, Experimental and numerical investigation on the motorcycle front frame flexibility and its effect on stability. *Mechanical Systems and Signal Processing*, Vol. 60–61, 452–471

Espie, S., 2010, Interaction between Powered Two-Wheeler Accidents and Infrastructure, Technical report, *2beSafe project*., Deliverable D1.2

Espie, S., Bekiaris, E., Nikolaou, S., 2010, Naturalistic rider studies for the analysis of riders behaviour and safety. International Conference "Road Safety on Four Continents", Abu Dhabi, UAE

Gabler, H.C., 2007, The risk of fatality in motorcycle crashes with roadside barriers. ESV: 20th international technical conference on the Enhanced Safety of Vehicles, June 18-21 2007, Lyon – France. Paper N° 07-0474. http://www.nhtsa.dot.gov.

Hublart, A., Subirats, P., 2013, Cinématiques des 2RM en chicanes et écluses

Laumon, B., 2002, Coordinated research on trauma after road traffic accidents and their causes and consequences. Final Report: Volume 1 - General Results. PREDIT 1996 – 2000, 292p

Majka, K., Blatt, A., Flanigan, M., 2007, Use of geocoded FARS data to analyse fatal motorcycle crashes. ESV : 20th international technical conference on the Enhanced Safety of Vehicles, June 18-21 2007, Lyon – France. Paper N° 07-0287. http://www.nhtsa.dot.gov

Miquel, G., 2002, Road safety: developing research to save lives. Information report No 29 drawn up on behalf of the Committee on Finance, Budgetary Control and Economic Accounts of the Nation. 2002-2003 regular session, annex to the minutes of the meeting of 23 October 2002. http://www.senat.fr

Ouelett, J.V., 2002, Environmental hazards in motorcycle accidents. Proceedings of the 26th annual meeting of the american association for automotive medicine, Ottawa, Ontario, Canada.

SETRA, 1992, Sécurité des routes et des rues, based guidelines.

SETRA, 2002, Guide pratique sur la signalisation verticale, based guideline

Slimi, H., Ichalal, D., Arioui, H., Mammar, S., 2013, Motorcycle maximal safe speed in cornering situation, Networking, Sensing and Control (ICNSC), *Presented at 10th IEEE International Conference*, The Hague

Slimi, H., Arioui, H., Nouveliere, L., Mammar, S., 2009, Advanced motorcycle-infrastructure-driver roll angle profile for loss control prevention, Intelligent Transportation Systems. Presented at 12th International IEEE Conference, St. Louis

Spacek, P., 2005, Track behavior in curve areas : Attempt at typology

Subirats,P., Violette, E., Hublart, A., 2011, Cinématique des 2RM sur les carrefours giratoires