STUDY OF CAR LOSS OF CONTROL ON A DYNAMIC SIMULATOR: CORRELATIONS BETWEEN SUBJECTIVE PERCEPTIONS AND OBJECTIVE PARAMETERS

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ABSTRACT

More than 30% of fatal car accidents in France are due to a loss of control. A study of this kind of accidents was hence carried out by the Laboratory of Accidentology, Biomechanics and human behavior PSA Peugeot-Citroën – RENAULT (LAB).

The experiment was conducted on the dynamic simulator of RENAULT with 124 subjects representative of the population involved in loss of control-induced accidents, depending on age and sex.

Real-time measurements were made both on the driver's actions (brake pedal travel, steering wheel angle...) and on car dynamics (yaw rate, speed, accelerations...). The subjects were asked to drive along a 30-km-run that ended with several critical situations, especially a right-oriented turn with low grip, very similar to a wet turn. Each subject had then to analyze the critical situation during an interview led by a psychologist. The subject was especially asked to describe his (her) own reactions, those of the vehicle, and his (her) feelings regarding safety and vehicle control.

This paper aims at relating objective and subjective data using two approaches, an analytical approach and an explanatory one.

In the first approach our task was to describe the vehicle dynamics and the driver's actions during the different stages of the loss of control. Each subject during the interview had defined these stages. We also extracted pertinent dynamic, geometrical, behavioral and perceptual variables that allow to differentiate LOC and non-LOC situations.

Using a more explanatory approach we could establish a statistical model explaining the driver's actions and his (her) perceptions concerning the behavior of the vehicle, as well as safety and danger during the critical situation, by objective and subjective parameters.

Our analysis pointed out that women turn more the steering wheel than men, while feeling something abnormal. Moreover, the least-experienced drivers have more severe dynamic driving conditions and the worst steering performance. It also appeared that the drivers who feel the most danger brake more and have greater steering

velocities. Finally, our observations lead us to the conclusion that the perceptual variables or the variables integrating the driver's actions seem to be more LOC and non-LOC discriminating than purely dynamic variables. Moreover the perceptual variables are the most pertinent ones concerning the feeling of danger.

Keywords

Accidentology, loss of control, dynamic driving simulator, ESP (Electronic Stability Program), vehicle dynamics, data analysis.

INTRODUCTION

The L.A.B is part of the two French car manufacturers, PSA Peugeot-Citroën and RENAULT.

The L.A.B.'s activities are dedicated to scientific knowledge about accidents, biomechanics and human behavior for a complete understanding of injury risks, as well as of how structural components, protection equipment and active safety systems operate and interact with human biomechanics and behaviors. The L.A.B.'s activities are divided into four areas: Accidentology, Active Safety (primary safety), Passive Safety (secondary safety) and Ergonomics (both cognitive and physical).

Several studies prove that approximately half of car occupants fatally injured in car accidents could not have been saved only by means of secondary safety (1). Therefore, a wide range of active safety systems, i.e. systems activated before the crash, are now implemented in order to help the driver avoiding a crash or reducing its severity. These systems must be triggered only if the driver actually needs assistance and must not interfere in normal driving situations. Once activated, they must take into account the driver's common behavior in order to limit unsuitable reactions and enhance insufficient reactions without being in conflict with the driver's natural behavior.

The design of active safety systems requires the determination of accident scenarios and data on how the driver actually behaves in these scenarios - see (2) and (3). It is necessary to define the system's triggering criteria and their action strategy. The determination of accident scenarios must rely on in-depth analysis of real world accidents. Once the most relevant scenarios have been determined, the driver's behavior in these scenarios can be studied by experiments conducted in driving simulator and on test tracks.

The specification of active safety systems requires the knowledge of the accident scenarios in terms of trajectory and dynamics of the vehicles, and in terms of the driver's cognitive processes. In order to get these data the L.A.B. has engaged a wide research program with the CEESAR (the French acronym for European Center for Safety Studies and Risk Analysis). Teams are collecting data on the scene accident. These data concern the vehicle, the road infrastructure and the driver (his or her perceptions, interpretations, decisions and actions).

Nevertheless these in-depth accident investigations provide few quantitative data on the driver's reactions. They can not provide data on the critical situations where the driver reacted efficiently and avoided the crash. These data can be obtained only by experiments artificially reproducing the accident scenarios identified. This is why, since 1997, the LAB has developed a research group devoted to the analysis of the common driver's behavior through Active Safety Experiments. These studies are conducted in driving simulators or on test tracks. In order to provide comprehensive results they involve more than a hundred common drivers representative of actual drivers in terms of age and sex.

Driving simulator experiments enable the analysis of very severe configurations that are not feasible on real scale. Moreover, these configurations are highly standardized, reproducible and configurable, as demonstrated in (4) and (5). Test track experiments are nevertheless necessary to validate simulator results, although they obviously require adapting the accident configurations for safety reasons.

Several experiments have been conducted following this process. The most recent ones concern loss of control (**LOC**)-induced accidents. Two LOC experiments have been conducted, one on a driving simulator (August 2000) and the equivalent one on a test track (September 2001). In this paper, we present some results based on the data collected during the LOC study in the driving simulator. To be able to work on solid, "geometrical" basis, we defined the LOC as a trajectory crossing the external road line.

In France, LOC-induced accidents represent 20% of personal injury accidents. This rate is close to 40 % in curves. Many active safety systems, in particular stability control systems such as the Electronic Stability Program (ESP), could significantly reduce the number of accidents following a LOC or reduce the seriousness of the injuries. One of the aims of the experiment was to explore the interactions between the ESP and the driver's actions on the steering wheel and on the brake pedal. Moreover the LAB decided to conduct a series of studies concerning the LOC (that is to say concerning mainly the *lateral* vehicle control) because they complete another series of studies focusing on the brake pedal actions (that is to say concerning *longitudinal* vehicle control) previously conducted by the L.A.B. – see (6).

The experiment was conducted on the dynamic simulator of RENAULT, involving 124 subjects representative of the population involved in LOC-induced accidents. Real-time measurements were made both on car dynamics and on the driver's actions. The subjects were asked to drive along a 30-km-run which ended with a wet turn. Each subject had then to analyze the critical situation during an interview led by a psychologist.

The present paper aims at relating objective variables (concerning the vehicle dynamics and controls) and subjective variables (anticipation, perception and feelings of the driver) collected during the experiment. The originality of our work is to incorporate a human-factor analysis in the process of functional specification and validation of active safety systems – see (3) and (7). Indeed, human factors have a great importance in the causal antecedents of an accident - the "Three-level" study pointed out that approximately 90% of the car accidents originate in human factors - (8) and (9). Moreover our own hypotheses concerning the role of human factors in car accidents are largely grounded on the models proposed by cognitive sciences to explain human errors and bias - see (10) to (13) - and a generic model of the driving task elaborated by the LAB and the CEESAR (3). Our work is then to relate, on the one hand, anticipations, mental representations and perceptions of the subject with, on the other hand, what he (she) does, how he (she) does it, its consequences and an *a priori* definition of his (her) tasks and what might be done to complete it. Furthermore, our experiments are carried out with non-expert and independent common drivers whereas the usual process is to use expert pilots. The idea is to draw more "ecologically valid" conclusions concerning the interaction between the driver and the active safety system.

In this paper two approaches are used: a descriptive one and a more explanatory one.

The first approach consists mainly of two tasks. First, we described the vehicle dynamics and the driver's actions during the different stages of the LOC (which are defined by the subject). Secondly, we tried to extract pertinent geometrical, dynamic and/or behavioral variables that allow to statistically differentiate LOC and non-LOC situations.

Using a more explanatory approach we tried to establish a statistical model explaining the driver's actions and perceptions (concerning his or her subjective safety and danger feelings during the critical situation as well as concerning the vehicle dynamics), by a set of objective and subjective variables.

EXPERIMENTAL PROTOCOL

General protocol

The experiment was conducted on 124 subjects representative of the population involved in LOC-induced accidents, depending on age and sex.

All the subjects were recruited outside the car manufacturers and were remunerated. Each test was planned to last for approximately three hours. The subject was told that he (she) came for a study concerning "ergonomics". Thus he (she) was possibly surprised by the LOC situation.

The first step was a medical examination that aimed at checking the ability of the subject to drive and to stand the simulator environment and the experimental conditions. Moreover visual tests and morphologic measurements were made.

The subject was then asked to drive for 15 minutes so that he (she) could familiarize with the simulator. The road track was real road, integrating road marks, signs and vehicle traffic. His (her) task was to drive as naturally as possible. After a 20-minute break, he (she) had to drive on a two-lane road, in an open country, under good conditions of weather and light and with little traffic. A member of the research team was seating beside the driver in the front passenger seat, monitoring both the speed and the driver's good physical conditions. The subject was asked to go for two runs, first a 30-km-long track and then a 5-km-long track. At the end of each of the two runs four critical situations were met. These situations were meant to produce LOC-induced accidents. We will describe them in detail later on. The sequence of the four different situations was changed between the two runs so that the subject reacted as spontaneously as possible.

After these two critical runs the subject was interviewed by a psychologist. He (she) was first asked to analyze the critical situations by describing his (her) feelings and his (her) actions, during the different LOC stages. Second, using the video recording, the subject could precisely determine when he (she) perceived that the vehicle reacted abnormally and when he (she) lost control of the vehicle. Eventually he (she) had to fill in a questionnaire concerning his (her) general driving habits.

The four LOC situations

The four critical situations met by the subject were the following: (FIGURE 1)

- going back from the verge to the road. The grip increases from 0.6g to 1g. It is usually referred to as a μ-split (μ-SPLIT);
- a left-hand curve with radius going abruptly from 200m to 100m, just like a narrowing turn on the road (NARROWING);
- a right-hand curve with radius 150m with very low grip on a short part of the turn ($\mu = 0.1g$), very similar to a patch of ice on the road (**ICE**). It is usually referred to as a μ -sprung;
- a right-hand curve with radius 150m with low grip all over the turn ($\mu = 0.35g$), very similar to a wet turn (**WET**).



FIGURE 1 Pictograms of the four situations inducing LOC.

These critical situations were chosen as the most representative LOC-induced accidents according to accidentologic studies. The grip values of each situation have been previously tuned in order to obtain approximately 50% of LOC in each situation.

In this paper we will only focus on the "WET" turn. This scenario resulted in the greatest LOC-accidents and is therefore the most statistically reliable.

MATERIAL AND MEASUREMENTS

Description of the simulator

The simulator used in this experiment was the RENAULT dynamic simulator. The car was based on a complete serial production Renault Clio mounted on a 6-DOF moving base having the same features as the commercialized version (steering wheel, gearbox...).

The simulator model was 3D and non-linear and could include road grip parameters, as well as the simulated Electronic Stability Program (ESP) developed by RENAULT. The vision system featured a projection onto three screens, covering a 150°x40° field of view. Engine, aerodynamics and tire noise were digitally synthesized (14). See FIGURE 2.



FIGURE 2 View of the RENAULT dynamic simulator.

Four cameras were mounted on the cabin, giving four images gathered into one using a Quad, recorded on a video tape recorder: (FIGURE 3)

- the feet of the subject (upper left corner);
- the face of the subject (upper right corner);
- the hands of the subject (lower left corner);
- the road (lower right corner).



FIGURE 3 An example of the video recorded during the driving task.

Objective Data

The vehicle was instrumented with sensors in order to measure in real-time the driver's actions in the cabin. Hence the simulator provided data both on car dynamics using its 3-D model (yaw rate, accelerations...) and on the driver's actions (brake pedal travel, steering wheel angle...). The numerical data were synchronized with the video data. We will now refer to these numerical data as "objective data" (TABLE 1).

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DRIVER REACTIONS	DYNAMIC VARIABLES
Brake pedal travel	The coordinates of the vehicle
Clutch pedal travel	Lateral distance (distance to the Lane)
Gas pedal travel	Roll angle
Gear shift lever position	Pitch angle
Steering wheel angle	Yaw angle
	Longitudinal speed
	Lateral speed
	Longitudinal acceleration
	Lateral acceleration
	ESP Activation State

TABLE 1 List of variables

Subjective Data

The subjective data stems from the interview led by the psychologist. First, the subject was asked to describe with his (her) own words what he (she) did, why and what he (she) felt about the reactions of the car during his (her) losses of control. The psychologist had previously selected one or two loss of control situations, depending on their severity, the spontaneity of the emotional reactions of the driver and on the interest of his (her) actions on the controls (concerning mostly the gas and brake pedals and the steering wheel). This selection was based on the brief examination of the videotape and on the indications given by the member of the team who accompanied the subject during his (her) test.

This first semi-structured interview of five to ten minutes was followed by a more structured one using the videotape of the test. The subject could point out precisely (with a 0.05s video precision) the moments when he felt that his (her) vehicle reacted abnormally, and when he (she) felt he (she) lost control, using the video recorder controls. The interviewer note the video recorder time codes corresponding to these moments. From now, we will call them:

- the ABNORMALITY moment (the corresponding time code, determined by the subject, will be called t_{ABN});
- the LOSS OF CONTROL moment (t_{LOC}).

Our analysis will be centered around these time codes, and we will use them to correlate subjective and objective variables, which is the aim of our study.

On the basis of multiple choice questions the subject was especially asked to describe his (her) own reactions and the reactions of the vehicle, his (her) feelings and what he (she) remembers he (she) did, as well as his (her) feelings regarding danger and his (her) own efficiency, for the ABNORMALITY moment (t_{ABN}) and the LOC moment (t_{LOC}).

The whole interview last for 40 minutes and was recorded. Finally a questionnaire provided data about the subject's general driving experience and habits, and about the realism of the simulator.

DATA OBTAINED FROM THE QUESTIONNAIRE	DATA OBTAINED FROM THE INTERVIEW
Sex	Perception of global efficiency
	• Yes, I was efficient
	• No, I was not
Age	Perception of danger at the different stages of LOC
	• Full safety
	Perceived Risk
	Acknowledged Danger
Driving experience	What were the reactions of the car at the different
The experience was measured as:	stages of LOC?
• the driving license date.	• The front of the car slipped to the left/right
• the annual mileage	• The rear of the car slipped to the left/right
	• The car went straightforward
	• The car zigzagged
	• The car slipped in "parallel"
	What were your own reactions, at the different
	stages of LOC?
	I accelerated
	• I decelerated
	• I broke
	• I released the clutch
	• I turned the steering wheel to the left/right
	• I geared

TABLE 2 List of the subjective variables

In the following we will study the objective data separately, by describing the vehicle dynamics and the driver's actions during the two stages of the LOC. Then we will relate the two sets of data (objective and subjective) in a more explanatory approach, thus establishing a statistical model explaining the driver's actions and perceptions.

DEFINITIONS OF NEW VARIABLES

A certain number of variables has been calculated on the basis of the set of variables listed in TABLE 1. These are purely *dynamic* and *geometrical* variables.

Nevertheless the driver's actions variables listed in TABLE 1 seemed not to characterize sufficiently the driver's behavior for they may be "too far removed from the perceptual cues that shape driving behavior and the way drivers evaluate driving performance" (15). This led us to explore, in parallel to the driver control and dynamic variables, a set of *behavioral* and *perceptual* variables. These variables have also been extracted from the initial set of data.

Dynamic variables

Slip angle

The slip angle of a vehicle is defined as the angle difference between the direction of the vehicle (the yaw vector), and its local trajectory (its speed vector).

Slip angle of the front and rear wheels

The slip angle of the wheels is defined as the angle difference between the direction of the tire, and its local trajectory, just like the slip angle of a vehicle. The variable depends on the speed of the vehicle, its slip angle and of course the steering angle of the wheels, giving the direction of the tire. We can find the mathematical formulae in (17) for instance, and hence calculate the slip angle of the front and rear wheels from our set of data.

Half-sum and Difference of the slip angles

It seemed pertinent to use the half-sum and the difference of the two slip angles thus calculated: the sum gets independent from the yaw rate and the difference gets independent from the slip angle.

Trajectory error angle

The trajectory error angle continuously gives the difference between the trajectory angle of the car, and the angle of the curvature of the road.

Lateral Acceleration-by-speed Product/Ratio

The combination of Lateral Acceleration and Speed is linked with the driving strategy for passing a curve (16). As a starting point, we chose the compute the product and the ratio of these two variables. Grossly, this strategy can be either "risk" (big lateral acceleration and speed) or "comfort" (small lateral acceleration and speed).

Geometrical variables

Lateral distance speed

This variable is the derivative of the *Lateral distance* variable. This variable appeared to be an easy-to-compute estimator of the speed of the approaching border line of the road. Other better estimators were computed (Time to Line Crossing).

Curvature/Radius difference

The *Curvature difference* is the difference between the observed curvature of the car and the 'ideal' curvature of the curve (1/150m), whereas, similarly, the *Radius Difference* is the difference between the observed radius of the car and the 'ideal' radius of the curve (150m).

Behavioral variables

This set of variables corresponds to variables defined as a combination of dynamic variables and driver's actions.

Steering wheel angle to Lateral distance Ratio

This variable is the ratio between the steering wheel angle and the lateral distance.

Steering wheel angle to Cancel the slip angle

Since the variable *Slip angle of the front and rear wheels* depends on the *car slip angle* and the steering angle (see (17)), we can set the two slip angles to zero in the equation, to obtain the *Steering wheel angle to Cancel the slip angle*.

Steering wheel angle Difference

This variable is the difference between the observed steering wheel angle, and the Steering wheel angle to Cancel the slip angle, hence giving the gap between the 'observed' behavior, and the 'ideal' one.

Yaw rate difference

This variable is defined as the gap between the yaw rate the driver should give to his (her) vehicle according to the steering angle (the "theoretical" yaw rate, calculated using car dynamics equations) and the yaw rate actually observed. The differences are due to grip discontinuity. The higher the difference is, the more the observed dynamics diverge from the intentional driver's actions, which means that the trajectory does not correspond to the driver's actions. This idea is fully based on the generic ESP activation algorithm: when the yaw rate difference gets greater than a pre-defined threshold, the ESP must be activated, hence decreasing the speed of one or two wheels. The exact determination of the threshold is made by the car manufacturer.

Perceptual variables

Perceptual slip angle

The slip angle of a vehicle is defined as the angle difference between the direction of the vehicle, and its local trajectory. Assuming that the driver pays attention to this slip angle and, at the same time, to the curvature of the road, we defined the *perceptual slip angle* as the angle difference between the direction of the vehicle, and the

'ideal' trajectory, that is to say the trajectory following the centerline (and not its real trajectory). The perceptual slip angle is then the difference between the Trajectory error angle and the car slip angle.

Apart from this variable, we created a series of variables based on the Distance to Line Crossing. From now we will refer to this set of variables as "LC-based variables".

Distance to Line Crossing (DLC)

The point where the car is supposed to cross the lane's border lines is geometricalally determined from 2Dgeometrical calculations, which we will not detail. The line can either be the left-side line or the centerline of the double-track road. Furthermore, it can be determined in the direction of the yaw vector or of the speed vector. It can also be calculated on the basis of a "predictive" Kalman filter-reconstructed trajectory. Distance to Line Crossing is the distance from the actual position to the estimated point of line crossing (FIGURE 4).

Time to Line Crossing (TLC)

The distance to Line Crossing and the instant speed being known, we can easily determine the Time to Line Crossing.

Degree of Emergency (DE)

Having the distance to line crossing we can calculate a degree of emergency based on the simplifying assumption that the driver will go straightforward. It is corresponding to a "purely longitudinal" degree of emergency, this latter being hereby defined as the minimum deceleration the driver should theoretically apply in order to reach the line with a zero speed, keeping the trajectory from its actual position to the point of line crossing.

Steering wheel angle to Distance to Line Crossing Ratio (RWDLC)

This variable is the ratio between the steering wheel angle and the distance to Line Crossing.



FIGURE 4 Definition of distance to Line Crossing (to the left-side line).

RESULTS

Descriptive approach

In this first approach we will describe the vehicle dynamics and the driver's actions during the different stages of the loss of control (that is to say at the moments referred to as t_{ABN} and t_{LOC}).

Given the fact that our subjective data set did not include time codes for drivers who did not lose control and that our aim was to compare the LOC and the non-LOC populations at the time codes, we then had to reconstruct time codes for the non-LOC population. For greater convenience, these reconstructed time codes will be referred to as the same name used for the LOC-population, that is to say t_{ABN} and t_{LOC} .

Our comparisons are based on a parametric test or on a non-parametric one (depending on the Gaussianity of the distributions of the variables studied): the Student test and the Wilcoxon test. The differences observed are illustrated by the corresponding histograms. They concern the maximum/minimum of the different variables. In all cases, we observed less overlap between the Loss of Control (LOC) and no Loss of Control (non-LOC) populations both at the moment of the subjective beginning of the loss of control (at t_{LOC}) and at the moment the subject feel the vehicle began to react abnormally (at t_{ABN}). This is due to more dispersion in the Loss of Control stage (LOC). The two populations are hence more differentiated at t_{ADC} than at t_{ABN} .

We here give the main results:

- The two *speed* distributions are much overlapped (T-test: p>0.05), especially at t_{ABN}. The values are greater in case of LOC : the modes at t_{ABN} are 80km/h and 100km/h, respectively for non-LOC and LOC population. The difference is significant at t_{LOC} (T-test: p=0.0001). Moreover the speeds are greater in the abnormality stage (ABN). This means that the trend for the driver is to decrease the speed of his (her) vehicle as he (she) goes from an abnormality (ABN) to a LOC feeling;
- The two *brake pedal travel* distributions (LOC and non-LOC) are quite similar, especially in the abnormality stage (Wilcoxon-test: p >0.1). In all cases, the mode is zero, which means that most of the people were not braking at t_{ABN}. To sum up, a few people had some braking action during the LOC (21 over 61);
- The two *lateral distance* distributions (FIGURE 5) are well separated (T-test: p=0.0001 at t_{ABN} and p=0.0001 at t_{LOC}): the *lateral distance* is a variable resulting from the LOC, since we defined the LOC as a trajectory crossing the centerline (or, a fortiori, the external road line). It entails that the subjects having lost the control had a rather good perception of when the LOC actually occurred. More interestingly, the subjects feeling something abnormal are actually drifting: lateral distance at t_{ABN} seems well correlated to the feeling of efficiency, as we will demonstrate it later;



FIGURE 5 Distribution of the LATERAL DISTANCE at t_{ABN}.

• The steering wheel angle (FIGURE 6) and the steering wheel velocity distributions are both very scattered. All subjects are turning the steering wheel to the right (since they are drifting out straight forward), with amplitudes going from 10° to 120° for the ABN stage, and from 10° to 320° for the LOC stage. The steering wheel velocity is also more important if the subject lost the control. Both at t_{ABN} and t_{LOC}, the LOC and non-LOC curves overlap so that what mainly differ between the two populations is the presence of statistical outliers (around 20%) whose steering wheel angle and velocity reach much higher values (Wilcoxon-test: p<0.0001 at t_{ABN} and at t_{LOC} , and for both variables);



FIGURE 6 Distributions of the Steering wheel angle and of the Steering wheel velocity at t_{LOC}.

• Concerning the *slip angle* distributions, despite the fact that the two distributions are a bit overlapped (but less than the speed or brake travel distributions for instance), the *slip angles* are greater in case of LOC (modes at 3° and 6°, Wilcoxon-test: p<0.001). The same could be said for the *slip angle of front and rear wheels* (Wilcoxon-test: p<0.001). Among all slip angle variables, the *difference of the slip angles of the front and rear wheels* (Wilcoxon-test: p<0.001). The same could be front wheels are greater than that of the rear wheels seems to be the most discriminating variable to differentiate LOC and non-LOC situations (FIGURE 7). The values of the slip angle of the car, slip angles of the front and rear wheels, and their difference and half-sum) the difference between LOC and non-LOC are statistically significant (T-test or Wilcoxon-test: p<0.0001). But among these parameters, the *difference of the slip angles* is a good indicator of the LOC since it is relevant as far as dynamics considerations are concerned and since the two populations are well discriminated;



FIGURE 7 Distribution of the Difference of the slip angles of the front and rear wheels at t_{LOC}.

• The *trajectory error angle* parameter (FIGURE 8) is discriminating because the two populations are quite well separated (the difference between the LOC and non-LOC populations is significant, T-test p<0.0001 at t_{ABN} and Wilcoxon-test, p=0.003 at t_{LOC}). The values are lower at t_{ABN} (modes at 1° in non-LOC case and 3° in LOC case) than at t_{LOC} (modes at 2° and 6°). The value at t_{LOC} is a LOC-induced parameter (since when losing control the vehicle understeers hence having an important trajectory error angle), whereas the value at t_{ABN} might be a predictive parameter, enabling the LOC and non-LOC discrimination.



FIGURE 8 Distribution of the Trajectory error angle at t_{ABN}.

Concerning the "LC-variables", that is to say the variables based on the *distance to Line Crossing* - the distance itself, the *Degree of Emergency (DE)*, the *Time To Line Crossing (TLC)* and the *Steering Wheel Angle To distance Ratio (RWDLC)* -, the two distributions are well separated, and the difference between most of these variables are statistically significant (Wilcoxon-test : p<0.0001 in almost all cases, whether at t_{ABN} or at t_{LOC}). This set of variables is then very discriminating. The speed-based and the yaw-based variables have very similar shapes and values (from now they will not be differentiated, unless explicitly), whereas the corresponding Kalman-based variables reach "lower" values, in terms of danger (lower degrees of emergency, greater distances or TLC). Generally, the *Degree of Emergency* is greater at t_{LOC} than at t_{ABN} (FIGURES 9 and 10).



FIGURE 9 Distributions of the Degree of Emergency at t_{LOC} (left) and of the TLC at t_{ABN} (right), both being defined from the distance to the left-side line, this distance being determined using a KALMAN filter.

• The two variables the *Steering wheel angle to Cancel the slip angle* and the *Steering wheel angle Difference* have very different discrimination powers. The first variable is not discriminating whereas the second one is very discriminating (Wilcoxon-test : p<0.0001). Indeed, the *Steering wheel angle Difference* really measures the gap between an 'ideal' angle and the real one observed, thereby integrating the driver's steering action, which leads to a better discrimination power (FIGURE 10).



FIGURE 10 Distribution of the Steering wheel Difference at t_{LOC}.

An explanatory approach

Using a more explanatory approach we could establish a statistical model relating the driver's actions and his (her) perceptions concerning the behavior of the vehicle, as well as safety and danger perception during the critical situation, by objective and subjective variables. The relations here described do not imply any temporal or causal relations because it is only statistical correlations between objective and subjective data.

In this purpose we used Mann-Whitney non-parametric statistical tests. The statistical Mann-Whitney tests (MW) compare one objective variable for different sets of the population in question, for example male and female drivers. The probability p of the Mann-Whitney test will be given for all 'a priori' driving factors (among which sex, age, driving experience) as well as for dynamic and perceptual factors (for instance rear slip, braking actions).

Influence of sex

We first tried to determine if differences concerning the dynamics variables and the driver's actions could be observed, depending on whether the driver was a woman or a man.

Some significant differences could be observed, concerning the *car speed*, the *steering velocity*, the *slip angle*, the *Steering wheel angle Difference* and the *Steering wheel angle to Distance to Line Crossing Ratio (RWDLC)*.

As far as dynamics variables are concerned we could establish that male drivers reach greater speed than women, both in ABN and LOC stages (MW, p=0.013 and 0.058, respectively). Moreover the *difference of the slip angles* is slightly higher for women (MW, p=0.087). Concerning the driver's actions, we observed that women turn more the steering wheel than men, while feeling something abnormal (MW, p=0.032). As far as geometrical variables are concerned, we established that the *lateral distance* is greater for male drivers in the abnormality stage (MW, p=0.006): male drivers are already more drifted out while starting to feel something abnormal. The *Steering wheel angle Difference* and the *RWDLC on the basis of the speed/yaw vector* is greater for women than for men at t_{ABN} (MW, p=0.029 and p=0.036 respectively). Most of these variables concern the steering actions.

Influence of age

Similarly we tried to determine the significant differences concerning the dynamics variables and the driver's actions, depending on the age of the driver. We divided our population into three categories: (a) Less than 35 years, (b) 35 to 50 years, (c) More than 50 years.

Some significant differences could be observed, especially concerning the following variables: *lateral acceleration, difference of the slip angles, yaw rate, Lateral Acceleration-by-speed Ratio, Steering wheel to cancel the slip angle* and *TLC to the centerline.*

The *lateral acceleration* is greater for less-than-35-year-old people (a) than middle-aged people (b) at t_{ABN} and in (a) than for the more-than-50-year-old people (c) at t_{LOC} (MW, respectively p=0.052 and 0.033). The *difference of the slip angles* is greater in the population (a) than in (b) (MW, p=0.011 at t_{ABN}) and in (a) than in (c) (MW, p=0.054 at t_{ABN} and p=0.071 at t_{LOC}). Finally, the oldest population (more than 50 years) has less *yaw rate* in the

LOC stage, and less *yaw rate difference*. Moreover the centrifugal *Lateral Acceleration-by-speed Ratio* is greater for the youngest population (MW, p=0.035 for (a) vs. (b); p=0.027 for (a) vs. (c)). Indeed, their centrifugal *lateral acceleration* is greater. In addition to this, the *Steering wheel to cancel the slip angle* is more important (steering to the left) for the most young compared to the oldest (MW, p=0.003). Finally, the speed-based *TLC* to the centerline at t_{LOC} is more important for the young category than for the old category (MW, p=0.028).

Influence of driving experience

In the same way we tried to determine the differences concerning the dynamics variables and the driver's actions, depending on the experience of the driver.

The experience was considered in terms of:

• the driving license date.

We used four categories: (a) Less than one year-old, (b) 1 to 5 year-old, (c) 5 to 10 year-old, (d) More than 10 year-old. Globally the *difference of the slip angles* tends to increase (MW, p<0.09 in all cases) as the driving license date gets older. Nevertheless, the amplitudes of this difference remain small.

As far as LC-based variables are concerned, the *Degree of Emergency* on the basis of speed/yaw is greater for less-than-5-year-experienced drivers than for 5-to-10-year-experienced drivers. Consistently the *TLC* (on the basis of speed/yaw) is lower. Finally, the *RWDLC* is lower for the subjects having their driving license for 5 to 10 years than that of less and more experienced drivers.

• the annual mileage

We used three categories: (a) Less than 5000 km per year, (b) 5000 to 15000 km per year, (c) More than 15000 km per year. The middle-experienced drivers have less *car* and *rear wheels slip angles* and less *yaw rate* (in ABN stage: less than the least-experienced drivers; in the LOC stage: less than the most-experienced drivers), as well as greater *gas pedal travel* in the ABN stage and greater *car speed* and *steering velocity* in LOC stage (MW, p<0.06 for all comparisons). They then have less dynamic solicitations, even if their actions on the vehicle are faster or "sharper". This means that the middle-experienced drivers category control their vehicle quite well despite an *a priori* "sharper" way of driving.

The *Lateral Acceleration-by-speed Ratio* reaches greater values in the centrifugal direction for the least-experienced drivers (MW, p=0.033 and 0.021) at t_{LOC} . Finally the *Steering wheel angle Difference* reaches greater values (right-steer) at t_{LOC} for the least-experienced drivers (MW, p=0.077 and 0.021): the steering performance of the least-experienced seems to be worse.

Consistently to the results concerning the driving license date, the least experienced drivers have greater *Degree* of *Emergency* (MW, p<0.02 in both cases). To sum up, the emergency observed at the moments pointed out by the less experienced is higher than that of the more-than-5000-km-per-year drivers. It means that either their emergency occurs earlier, or that they detect emergency earlier.

Influence of the perception of global efficiency

We also tried to determine the significant differences concerning the dynamics variables and the driver's actions, depending on the driver's perception about the efficiency of his (her) actions during the LOC.

On the one hand the more efficient the driver thought to be, the greater *the difference of the slip angles* is (MW, p=0.075). On the other hand - and more interestingly - , we observed that the more efficient the driver thought to be, the smaller the *lateral distance speed* was in the ABN stage, *and* the greater (more negative) it was in the LOC one (MW, p=0.047 in each case). From the driver's point of view, the main issue for the driving task may be to keep a *satisfactory* lateral position, especially being quite far at low speed from the line before any LOC, and moving at faster speed away from the approaching line during the LOC.

Influence of the perception of global danger

We also tried to determine the significant differences concerning the dynamics variables and the driver's actions, depending on the driver's perception about the level of danger, using three categories: (a) Full safety; (b) Perceived Risk; (c) Acknowledged Danger.

As far as the dynamics variables are concerned we could establish that the *difference of the slip angles* is greater for the population who acknowledged danger (c), compared to the populations who felt safe (a) or just perceived risk (b), in ABN stage (MW, p=0.031). Concerning the driver's actions, we observed that the trend for the subjects feeling the most danger is to brake more (MW, p=0.013 and 0.082 at t_{ABN}). Furthermore, the more danger is perceived, the greater the *steering velocity* is (MW, p=0.012 and 0.065 at t_{ABN}). This is true in ABN and LOC stages. Moreover the difference between (c) and (a) and between (b) and (a) is significant: we observed a little travel of the clutch pedal (the foot is on the pedal) vs. a zero-pedal travel, respectively p=0.031 and 0.014 at t_{LOC} . It means that the subjects who acknowledged a danger have their foot on the clutch pedal whereas the other two populations do not, whether in ABN or LOC stages.

During the ABN stage, the *Degree of Emergency* (*DE*) to the centerline based on Kalman filtering is more important for the population who declared feeling the most danger (MW, p=0.037 and p=0.03). Consistently, their *Time to Line Crossing* (*TLC*) to the centerline is lower (MW, p=0.042 and p=0.025) and the *Steering wheel angle to Distance to Line Crossing Ratio* (*RWDLC*) to the centerline is greater (MW, p=0.038 and p=0.021). All these variables are Kalman-based: during the ABN stage, the Kalman prediction possibly suits well the trajectory prediction made through the mental process of the driver. Moreover, the line concerned here is more often the centerline than the left-side line: the perception of danger starts with the approaching centerline, the people hence less concentrating on the external left-side line.

During the LOC stage, the *DE* and the *RWDLC* are lower for the people who perceived (b) or acknowledged danger (c) (MW, p=0.036 and p=0.031 for the *DE*; p=0.036 and p=0.044 for the *RWDLC*), and their *TLC* is greater (MW, p=0.043 and p=0.041). This surprising result can be due to the fact that the people who perceived or acknowledged danger had already crossed the centerline so that the little values observed for these two categories actually correspond to the car moving away from the centerline, not approaching it.

Influence of the perceived slip of the front/rear of the car (to the left)

We first tried to determine if differences concerning the dynamics variables and the driver's actions could be observed, depending on whether the driver felt the front of his (her) vehicle slip to the left (n=10 at t_{ABN} , 9 at t_{LOC}) or not (n=50 and 51).

• Concerning the subjects who perceived a slip of the front of the car :

During the ABN stage, we observed a more important *yaw rate* at t_{LOC} and a more important *slip angle of the rear wheels* at t_{LOC} (MW, p=0.01 and p=0.075 at t_{ABN} ; p=0.05 and p=0.06 at t_{LOC}). They also have lower *Steering wheel angle to cancel the slip angle* at t_{LOC} (MW, p=0.009). Furthermore, the *perceptual slip angle* at t_{LOC} is greater (MW, p=0.026). Finally, these subjects also have lower *Curvature and Radius Differences* at t_{LOC} (MW, p=0.004 and 0.005). It means that the feeling of slip does not seem to have much to do with how much the actual trajectory differs from the ideal one.

During the LOC stage we also observed a more important *slip angle of the car* (at t_{ABN} and t_{LOC}) and a more important *yaw rate difference* at t_{ABN} (MW, respectively, p=0.088, p=0.067 and p=0.036). Similarly, during the LOC stage, the *perceptual slip angle* at t_{ABN} (MW, p=0.048) and at t_{LOC} (MW, p=0.070) are greater and the *Curvature and Radius Differences* at t_{ABN} are lower (MW, p=0.043 and 0.05). They also have lower *Steering wheel angle to cancel the slip angle* at t_{ABN} (MW, p=0.011). Consistently, the same variables appear either on the ABN stage, or on the LOC stage.

• Concerning the subjects who perceived a slip of the <u>rear</u> of the car :

We also observed more important *slip angle of the car*, *yaw rate* and *slip angle of the rear wheels* (at t_{LOC} for all the three parameters), among the subjects who felt a slip of the <u>rear</u> of the car at t_{ABN} (n=50) and at t_{LOC} (n=51): respectively for each parameter at t_{ABN} and t_{LOC} (MW, p<0.06 in all cases).

The people having felt the rear of the car slip have greater *Curvature Difference* and greater *perceptual slip angle*. Concerning the LC-based variables, their *DE* (*TLC* respectively) to the centerline on the basis of Kalman filtering is lower (respectively greater), at t_{LOC} . At t_{ABN} , their *RWDLC* is lower.

In both front and rear slips, the common variables in slip perception are hence: *yaw rate, car slip angle of the rear wheels, Curvature and Radius Differences* and *perceptual slip angle*. This tends to prove that the results above are consistent, the same dynamic perceptions being explained by the same dynamic objective variables.

Influence of the perceived "parallel" slip of the car

We tried to determine if differences concerning the dynamics variables and the driver's actions could be observed, depending on whether the driver felt the whole vehicle slipping "in parallel" (n=29 at t_{ABN} , 36 at t_{LOC}) or not (n=31 and 24).

Some statistically significant differences could be observed in both ABN and LOC stages, concerning the following variables: car speed, difference of the slip angles, perceptual slip angle, Steering wheel angle difference, and RWDLC.

We observed a more important *yaw rate* at t_{LOC} for the subjects perceiving a parallel slip. The speed is also higher in both ABN and LOC stages for these subjects (MW, p=0.03 and 0.019 at t_{ABN} , p=0.026 and 0.048 at t_{LOC}). The same observation can be made for the *difference of the slip angles*. Moreover, the *trajectory error angle* is higher at t_{LOC} for the subjects having felt a parallel slip in LOC stage (MW, p=0.015). Finally, the *steering wheel angle* is less important at t_{ABN} for the subjects having felt a parallel slip in ABN stage (MW, p=0.024), and becomes more important at t_{LOC} for the subjects having felt a parallel slip in LOC stage (MW, p=0.016). This maybe due to the fact that the subjects perceive the parallel slip of the car later, and to react to it. Finally, the *perceptual slip angle* at t_{LOC} for the people feeling a parallel slip of the car during both stages is lower (MW, p<0.02), as well as the *RWDLC*, *both* at t_{ABN} and at t_{LOC} (MW, p<0.04). Moreover, the *Steering wheel angle difference* is lower at t_{ABN} (MW, p=0.025) and greater at t_{LOC} (MW, p=0.014): the steering performance of the people who do not feel a parallel slip might be better when losing control.

Influence of the deceleration

We tried to determine the differences between the drivers who decelerated (n=8 at t_{ABN} , 36 at t_{LOC}) and those who did not (n=53 and 24).

The subjects who decelerated in the LOC stage have greater *trajectory error angle* at t_{ABN} (MW, p=0.065): a big *trajectory error angle* in the ABN stage may imply a deceleration which occurs in the LOC stage because of reaction time. In addition to this, they have greater *steering velocities* to the right during the ABN stage (MW, p=0.022).

During the LOC stage the subjects who decelerated have greater *Curvature Difference* at t_{LOC} (MW, p=0.069): a better trajectory is observed for people who did not decelerate.

Moreover during the ABN stage they have greater *DE* and lower *TLC* (to the <u>left-side line</u>, using Kalman filtering) at t_{ABN} (MW, p=0.022 and 0.024), and during the LOC stage they have greater *DE* and lower *TLC* (to the <u>centerline</u>, using Kalman filtering) at t_{ABN} (MW, p=0.022 and 0.024). Consequently, the people decelerating while feeling something abnormal ("the fast-response people") seem to be sensitive to the left-side line (a relatively "far" danger), whereas the people decelerating while losing control ("the slow-response people") are just sensitive to the centerline (a very "close" danger). More concisely, people having a fast response are far-sighted.

Influence of the acceleration

We tried to determine the differences between the drivers who accelerated during the ABN stage (n=15) and those who did not (n=46).

The subjects who accelerated in ABN or LOC stages have less *trajectory error angle* at t_{LOC} (MW, p=0.048 and p=0.051) and lower Kalman-based *DE* to the left-side line (MW, p=0.066). Furthermore, the subjects who accelerated in the ABN stage have *steering velocities* at t_{LOC} corresponding to a steer to the left whereas those who did not accelerate steer to the right (MW, p=0.06).

This set of results can be explained by the fact that these subjects are not yet in a loss of control situation (we observed they have less trajectory error), hence passing the curve normally, with usual small trajectory corrections on the steering wheel. People accelerating have less trajectory error angle, which means that they

have a better trajectory, thus implying that their Kalman-predicted trajectory is better and that their DE to the left-side is lower.

Influence of the braking action

We tried to determine the differences between the drivers who braked (n=21 at t_{ABN} , 24 at t_{LOC}) and those who did not (n=40 and 37).

Some statistically significant differences could be observed in both ABN and LOC stages, concerning the following variables: *lateral acceleration* and lateral acceleration-based variables, as well as *perceptual slip angle* and *trajectory error angle* (apart form the trivial *brake pedal travel* variable).

Both in ABN and LOC stages, the subjects who braked have less centrifugal *lateral acceleration* (in both sequences) – indeed their speed is lower. Moreover they have less *roll angle* (towards the exterior of the curve) at t_{ABN} and at t_{LOC} (MW, p<0.05). Finally, the *Lateral Acceleration-by-speed Product* and *Ratio* are less negative for people who had braked (MW, p<0.03), always because of less speed.

The *perceptual slip angle* at t_{LOC} is lower for people having braked during the ABN stage (MW, p=0.011) and greater for people having braked during the LOC stage (MW, p=0.061), whereas the *Trajectory error angle* at t_{LOC} is greater (MW, p=0.055).

CONCLUSION

The design of active safety systems requires data concerning accident scenarios and the behavior of drivers in these situations. Scenarios can be determined by in-depth accident investigations. Experiments conducted in driving simulators and on test tracks enable to complete this data and to analyze the behavior of common drivers.

The purpose of our experiment was the study of LOC-induced accidents in the Renault dynamic simulator. The present study aimed at relating objective variables (concerning the vehicle dynamics and the regulations on the car controls) and human factors (socio-demographic variables, expertise, anticipations, perceptions and feelings of the driver). Our analysis pointed out that, for the LOC-population:

- male drivers reach greater speed than women;
- women turn more the steering wheel than men, while feeling something abnormal. More generally, most of the variables differentiating male and female drivers concern the steering wheel;
- least-experienced drivers have more severe dynamic driving conditions (their *lateral acceleration* and their *difference between the slip angles of the front and rear wheels* are greater);
- the emergency at the different stages of the LOC pointed out by the least-experienced drivers is greater;
- the middle-experienced drivers (5000 to 15000 km per year) have less dynamic solicitations (lower *car* and *rear wheels slip angles* and lower *yaw rate*) even if their actions on the vehicle are faster or "sharper" (greater *gas pedal travel, car speed* and *steering velocity*);
- the least-experienced drivers seem to have the worst steering performance (their *Steering wheel angle Difference* reaches greater values);
- from the driver's point of view, the main issue for the driving task is to keep a *satisfactory* lateral position, especially being quite far (slowly) from the line before any LOC, and moving (fast) away from the approaching line during the LOC;
- the drivers who feel the most danger have higher *differences between the slip angles of the front and rear wheels*. They brake more and have greater steering velocities; finally they have their left foot on the clutch pedal, being ready to jump onto the brake pedal;
- the perception of danger starts with the approaching centerline, the drivers possibly being less concentrated on the external left-side line;
- when the driver feels the slip of the front/rear of the car (to the left) it seems to be mainly due to high *yaw rate*, *car slip angle of the rear wheels*, *curvature* and *radius difference* and *perceptual slip angle*. Especially it does not seem to have much to do with the « quality » of the trajectory;
- when the driver feels the "parallel" slip of the car the *wheels slip angles difference, perceptual slip angle, steering wheel angle difference* and the *trajectory error angle* are greater;
- the drivers having decelerated have greater steering velocities to the right;
- the driver decelerating early seems to be sensitive to a relatively "far" danger, whereas the driver decelerating later is sensitive to a "close" danger. More concisely, people having a fast response are far-sighted;
- one of the driver's reactions during the understeer is to try to shorten their speed, which is illustrated by the deceleration or the braking actions.

Concerning the variables themselves it also appeared that:

- among all the slip angle variables, the *difference of the slip angles of the front and rear wheels* seems to be the most discriminating variable to differentiate LOC and non-LOC situations;
- the Kalman prediction might suit well the trajectory prediction made by the driver;
- the *Degree of Emergency*, the *Time to Line Crossing* and the *Steering wheel angle to Distance to Line Crossing Ratio* are much correlated with the feeling of danger. It fully validates our LC-based variables;
- in all cases our observations lead us to the conclusion that the perceptual variables or the variables integrating the driver's actions seem to be more LOC and non-LOC discriminating than purely dynamic variables. Moreover the perceptual variables are the most pertinent ones concerning the feeling of danger, since they more estimate the pertinent stimuli belonging to the cognitive process. Still, the geometrical variables are also important, maybe because of the simulator environment.

The present analysis of the driver's behavior and perceptions in accident situations may give a better understanding of the regulation strategies on the car's controls, particularly on the steering wheel, as well as providing data for the determination of triggering criteria and control strategies of systems like the ESP. In order to validate the results based on the Simulator experiment, the LAB is conducting another experiment concerning LOC-induced accident. It will be carried out with common drivers on a test track in three different road configurations, among which a wet turn.

However the specification of active safety systems cannot rely exclusively on accident data. This is why a campaign of measure is planned concerning transversal regulation of the car on open road, with common subjects and a "common driving" task. Indeed, the knowledge of the driver's behavior in normal driving situations is necessary in order to be sure that the systems will not assist drivers when they do not need it. This is required for a good acceptability of those systems and consequently for their efficiency to reduce the number of accidents.

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