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Test methodology for the vehicle-tire handling performance evaluation: objectification of driver's subjective assessment

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Abstract: In the context of vehicle-tire handling performance evaluation, subjective closed loop and objective open loop vehicle dynamics tests have been carried out in linear domain to get insights on the driver's testing strategy. Experimental tests data analysis shows that vehicle responses have a big effect on the driver's steering input and, therefore, on the subjective rating. In this paper, a clustering method in accordance with the test driver is developed to group, categorize and differentiate specific vehicle-tire handling behaviors. This method allows to study the correlation between objective measurements and subjective evaluation of the vehicle responses. Data analysis highlights objective metrics that can explain the variance of the driver's subjective rating. The handling performance classification developed by the driver can be retrieved with the objective metrics previously mentioned.

Keywords: Driver behavior, vehicle dynamics, data reduction.

1. INTRODUCTION

In the automotive field, the handling performance of a vehicle-tire system is crucial as it involves safety and driving pleasure. Professional drivers evaluate the vehicle behaviour under a variety of demands and provide a subjective rating for the items evaluated using a subjective questionnaire. A consistent and smooth vehicle response following an input on the steering wheel is the handling behaviour targeted by the customer. This explains why the characterization of handling is one of the main challenges for car manufacturers. The tire plays an important role in the definition of the vehicle system handling behaviour as it is the main responsible of ensuring the efforts' transmission between the vehicle and the ground (Pacejka (2006)). The handling performance of the vehicle-tire system can be assessed with objective open loop (steering wheel input is fixed during the maneuver; the driver acts as a robot) and subjective closed loop (driver is part of vehicle/tire system and he acts as a controller following the maneuver constraints) measurements on dry and wet asphalt.

In (Kim and Yoon (2015)), the authors attempted to extract the main objective parameters which have high correlation with the subjective assessment of steering feel. For the subjective assessment, a survey sheet specifically designed for the correlation of objective parameters was used, however no indications about the design of this specific survey have been provided. Based on this specific survey, in (Kim and Yoon (2015)) it is stated that on-center feel and steering response are the main performance items in the evaluation of steering feel. Hence, the first steps of this study were to demonstrate how system's dimensions reduction as well as the selection of relevant subjective/objective maneuvers can lead to improve the consistency of the subjective assessment. This is one of the main conclusions in (Gmez et al. (2015)). This study focuses on the knowledge improvement of the correlation between objective measurements and the subjective assessment and how to use this knowledge to move towards efficient handling performance evaluations. Authors used a word counter to identify key parameters from the subjective assessment comments showing that different words might be used to describe the same subjective feeling of performance. The present study confirms these findings and highlights the importance of this approach to improve the consistency of the subjective assessment. Another important step of this study is the selection of the most relevant objective open loop maneuvers. In (Israr et al. (2009)), it is stated that humans can robustly identify the natural frequency of a second order system and excite it at his natural frequency even when the magnitude cues (gains) are changed. For this reason, modelling the vehicle responses resulting from a steering input with a transfer function, is a plausible approximation method (e.g. Badji et al. (2009)).

This paper is structured as follows. Section 2 describes the testing methodology: The Principal Component Analysis, the subjective /objective correlation analysis and the system transfer functions analysis, are presented in Section 2. Results on the objective/subjective correlation and the importance of the driver's input as well as vehicle responses are presented in Section 3. In Section 4, the results are extensively discussed, commented and compared with previous findings from the literature. In (Gmez et al. (2015)) the correlation study between the objective metrics and the subjective assessment highlighted that drivers' behaviour can be classified based on different kinesthetics and/or vestibular stimulus sensitivities. In this paper, additional objective metrics directly linked with specific kinesthetic and vestibular stimuli are proposed.

2. TESTING METHODOLOGY

Since the handling performance of the vehicle-tire system is mainly carried out subjectively by professional test drivers, the subjective survey for the evaluation has been analyzed. The subjective survey includes more than 20 items and, in order to reduce the complexity, the possibility of problem dimension reduction has been investigated by using the Principal Component Analysis algorithm.

2.1 Principal Component Analysis applied on the subjective test questionnaire

PCA (see Jolliffe and Springer-Verlag (2002)) is a dimensionality reduction algorithm to find a more meaningful basis for a set of data. It is used when we need to tackle the dimensionality reduction among data with linear relationships, where having too many dimensions (features) in the data causes complexity and difficulties especially when features have different scales. PCA algorithm has been applied to driver's subjective ratings for the items in the above-mentioned subjective survey (Zimmer (2019)) and the main items' clusters have been identified.

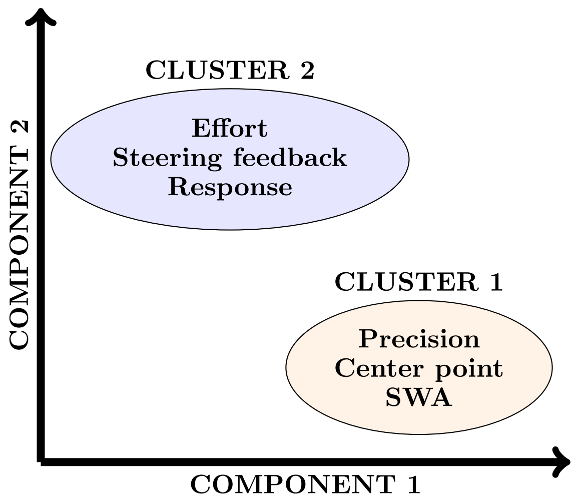

Fig. 1. System's dimensions reduction with PCA

Results of the PCA (Fig.1) for 44 different tire constructions tested in the linear domain (same vehicle, same driver, same testing surface, same temperature conditions used), showed that 2 main clusters can be identified:

- CLUSTER 1: Vehicle Yaw Response at small steering wheel angles (up to 10°) called RESPONSE AROUND 0;
- CLUSTER 2: Vehicle Yaw Stability (steering wheel angles up to 30°) called RESPONSE LINEARITY AFTER 0;

The PCA indicates that high values of COMPONENT 1 & COMPONENT 2 are linked respectively with high values of CLUSTER 1 & CLUSTER 2. The first two principal components can explain the 93% of the variance of the multidimensional system. Fig 2 shows the re-distribution of the data points according to the two principal components as well as the contribution of the identified clusters on the definition of those.

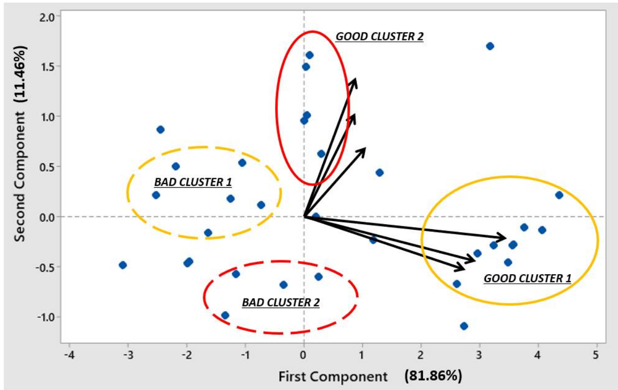

Fig. 2. Redistribution of data points according to the 2 main components

To validate and generalize the findings, 10 other professional test drivers have been filmed while performing a handling performance evaluation test. Visual inspection of the videos and subjective comments analysis have shown that two clusters of the subjective questionnaire identified with the Principal Component Analysis are the main items assessed by the professional drivers (CLUSTER 1 & 2). In addition to that, all the drivers have used the same 2 subjective maneuvers for the assessment of the two main subjective items (main system's clusters). These two subjective maneuvers are described in the next section.

2.2 Selection of relevant subjective closed loop maneuvers

Drivers have used a sinusoidal steering wheel input maneuver for the evaluation of CLUSTER 1 (Fig. 3) and a step steering wheel input maneuver for the evaluation of CLUSTER 2 (Fig. 4).

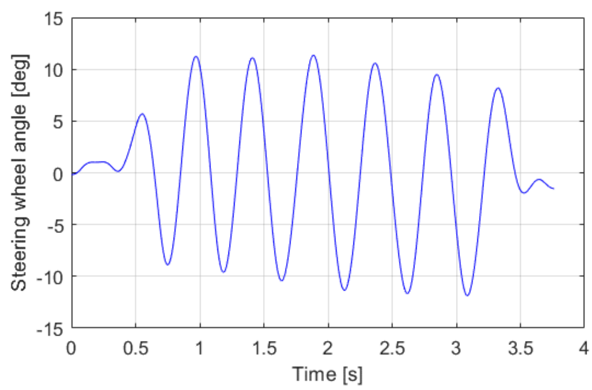

Fig. 3. Sinusoidal steering wheel input for CLUSTER 1

Therefore, in this study the 2 maneuvers described above have been used as subjective closed loop maneuvers.

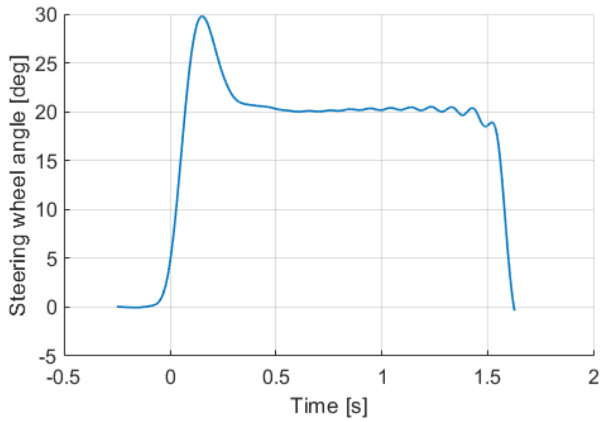

Fig. 4. Step steering wheel input for CLUSTER 2

The driver was asked to test 17 tire constructions in the above-mentioned testing conditions, performing the 2 main maneuvers and to provide his rating for the 2 principal clusters identified. Blind test methodology has been used for the testing sessions. As in Gmez et al. (2015), the blind test methodology is used to investigate subjective assessments of vehicle handling and steering feel tests, both numerical and verbal, to understand drivers' use of judgement scales, rating tendencies and spread.

The driver was also asked to characterize statistically each tire construction by performing several times the same maneuver. In addition to that, the driver used a specific strategy for the handling behavior classification (Zimmer (2019)). In this paper, the analysis focuses on the sinusoidal steering input maneuver. Vehicle responses and steering inputs (steering wheel angle and steering wheel torque) have been recorded while the driver was performing the test.

2.3 Handling Behavior Classification

In addition to the subjective ratings provided by the driver for the 2 main clusters' evaluation, the driver has provided a classification of the handling behaviour as well. Since two main components have been identified as representative of the handling performance, 4 main handling behaviors can be classified (Fig. 5):

This clustering strategy, proposed by professional driver, aims to facilitate the subjective evaluation of handling performance providing useful info on the performance classification. Basically, the driver can evaluate the two components by performing specific subjective maneuvers. Then, the driver synthetizes and merges the evaluation of the 2 main components by selecting a specific handling behavior (Fig. 6).

2.4 Objective open loop maneuvers

Based on the $ISO-7401$ standard, the test is performed to determine the transient response behavior of road vehicles (frequency domain). This test can be performed by a robot or by a professional test driver. In this study, the test was performed by a test driver with more than 25 years of experience in objective open loop testing. The driver acts as a robot (steering wheel input is fixed) and must

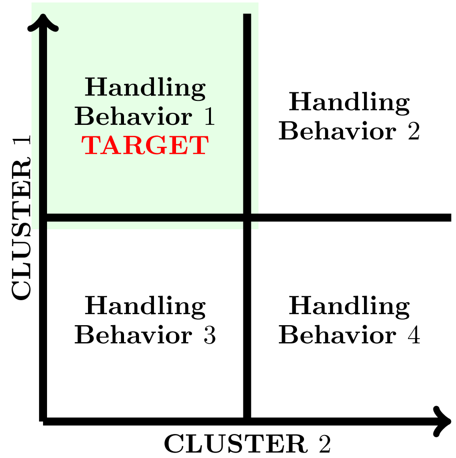

Fig. 5. Handling behaviors classification

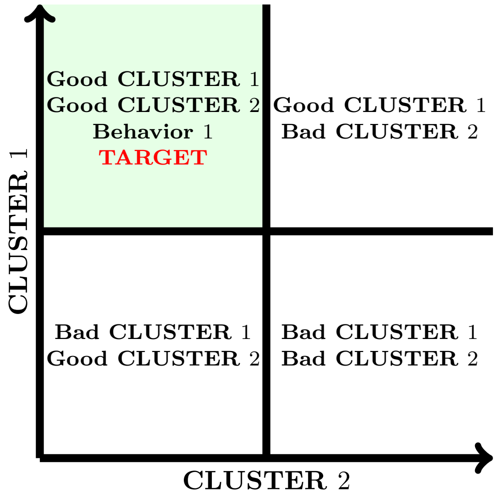

Fig. 6. Handling behaviors classification based on subjective evaluation results

respect constraints on the steering wheel angle frequency (frequency linearly increasing from $0.2Hz$ up to $3.5Hz$) and on the steering wheel angle magnitude ($\pm 20°$). Here below in the Fig.7, a time representation of the maneuver is shown:

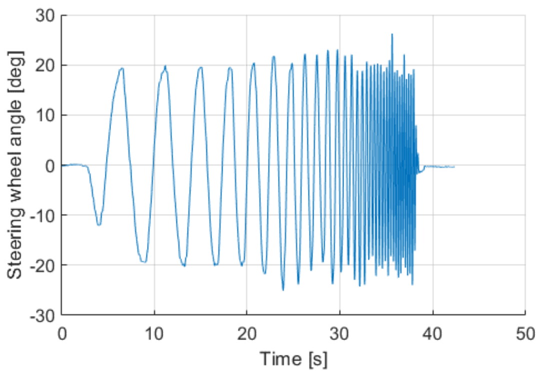

Fig. 7. ISO 7401 Extract from Lateral transient response test methods (Open-loop test methods) sinusoidal sweep

The 17 tire constructions (different brands, different sizes and different segments) have been tested using this procedure in the above-mentioned testing conditions, to obtain the transfer functions related to the steering wheel input and the vehicle responses. Particular attention has been paid on the temperature conditions of these tests to match with the temperature conditions of the subjective closed loop tests. The transfer functions (gain & phase delay) are obtained as a Fast Fourier Transform ratio between output and input signals. Hence, the 2^{nd} order system theory is used to model the dynamic response of the vehicle-tire under different excitation frequencies (remaining in the linear domain for the tire usage) e.g. (Rajamani (2006)).

2.5 Post-Processing Objective & Subjective maneuvers

Post-processing of the objective open loop maneuvers (described in Subsection 2.4) has provided the transfer functions gains and phase delays. The post-processing of the subjective closed loop maneuvers has been carried out in the time domain and focused on the identification of signals' shapes, delays, peaks, stabilization times, frequency. 2^{nd} order system theory and Lissajous Curves have been respectively used to analyse the step steer and the sinusoidal maneuvers identified in Subsection 2.2.

2.6 Correlation analysis Subjective closed loop measurements & driver's subjective ratings

A linear regression and Pearson's correlation analysis (Altman et al. (2013)) between the subjective closed loop measurements and the driver's subjective ratings for the CLUSTER 1 has been performed. The goal was to identify the main metrics from the post-processed subjective closed loop measurements linked with the driver's subjective ratings. The correlation analysis shows that objective metrics related to the steering wheel input (torque and angle) and vehicle responses are characterized by a coefficient of determination (R^2) $> 80\%$ and a coefficient of variation $< 5\%$. Therefore, these metrics are selected as key objective metrics.

2.7 Merging subjective closed loop measurements and objective open loop measurements at Driver's working point on transfer functions of interest

Based on the results of Subsection 2.6, the subjective closed loop metrics of interest can be merged with the post-processed objective open loop measurements (transfer functions). By doing so, it is possible to identify a working point on the transfer function selected by the driver. This identified working point on specific transfer function will allow us to understand the driver's testing strategy as well as the main vehicle responses he captured during the subjective evaluation. This methodology highlights the importance of the driver's input for the definition of the vehicle responses and it is a crucial point for the vehicle - driver interaction understanding while studying the subjective-objective correlation.

3. RESULTS

Results of the correlation analysis between the subjective closed loop metrics and the driver's subjective ratings for the evaluation of CLUSTER 1 (Subsection 2.6) shows that the main metrics to retain (coefficient of determination (R^2) $> 80\%$ and a coefficient of variation $< 5\%$) are related to the steering wheel angle frequency applied by the driver (Fig. 8). In addition to that, the delay between the steering wheel inputs (steering wheel torque and steering wheel angle) and the vehicle roll response results to be significant as well. Since we focus on the sinusoidal steering input for the evaluation of CLUSTER 1, results highlighted the importance of the steering wheel input frequency chosen by the driver. This steering wheel input frequency varies from $1.6Hz$ up to $2.3Hz$ and correlated well with the driver's subjective rating for the CLUSTER 1 (p value < 0.05).

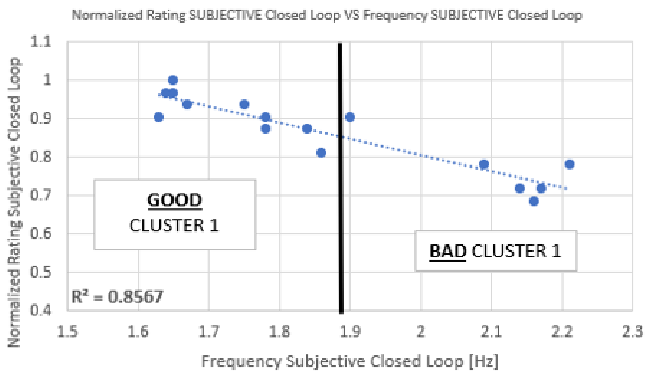

Fig. 8. Correlation between the Normalized Rating for the subjective closed loop and the frequency chosen by the driver during the subjective closed loop

It has been noticed that the frequency chosen by the driver changes according to the tire construction tested and is used to identify a specific working point on the transfer functions roll angle - steering wheel angle and roll angle - steering wheel torque. These two specific transfer functions have been selected based on the results of the correlation study mentioned above. The analysis of the delay between roll angle and steering wheel angle at the frequency chosen by the driver in the subjective closed loop maneuver shows that this delay is correlated with the frequency chosen by the driver (Fig.9). However, this delay cannot gauge performance and differentiate between a good and a bad evaluation of the CLUSTER 1 (an unequal variance t-test has been selected to check for statistical difference e.g. (Ahad and Syed-Yahaya (2014)). For all the tire constructions tested, the phase delay seems statistically constant around 90° (signals in quadrature) independently of the frequency and independently of the handling behaviour.

The analysis of the delay between roll angle and steering wheel torque at the frequency chosen by the driver in the subjective closed loop maneuver shows that this delay is perfectly correlated with the frequency chosen by the driver (Fig.10). In addition to that, this delay can gauge performance and differentiate between a good and a bad evaluation of the CLUSTER 1 (an unequal variance t-test has been selected to check for statistical difference). It has also been noticed that the bigger is the delay between the steering wheel torque input and the vehicle's roll response the better is the subjective evaluation of the CLUSTER 1 (higher driver's rating Fig.11).

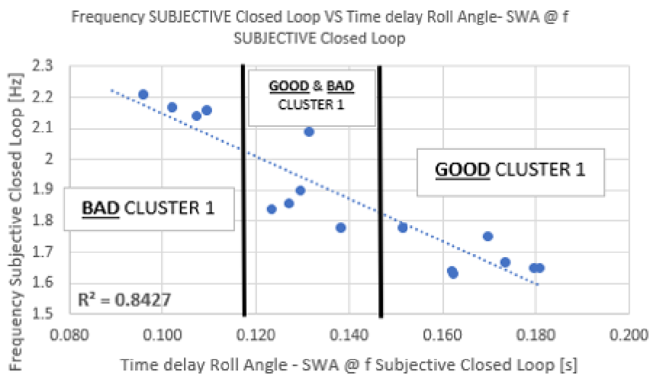

Fig. 9. Correlation between frequency chosen by the driver for the evaluation of CLUSTER 1 (sinusoidal steering input) and the resulting phase delay at that specific frequency in the roll angle - steering wheel angle transfer function

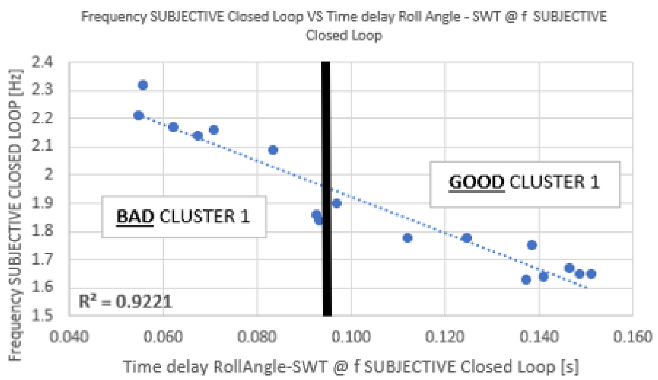

Fig. 10. Correlation between frequency chosen by the driver for the evaluation of CLUSTER 1 (sinusoidal steering input) and the resulting phase delay at that specific frequency in the roll angle - steering wheel torque transfer function

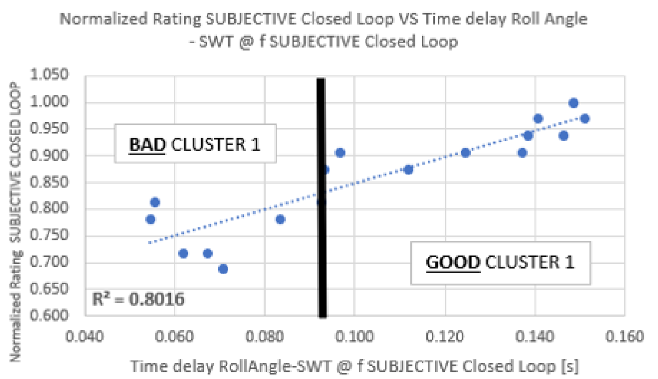

Fig. 11. Correlation Normalized Rating for the subjective closed loop evaluation (CLUSTER 1) and the resulting phase delay at that specific frequency in the roll angle - steering wheel torque transfer function

4. DISCUSSION

Data analysis shown in the Results section highlights an importance of the frequency chosen by the driver for the study and a good understanding of the driver's subjective closed loop evaluation. This finding indicates that changes related to the dynamics of the vehicle-tire system can induce a different driver's motor adaptation. In (Israr et al. (2009)), authors explored the effects of magnitude and phase cues on human motor adaptation demonstrating that participants were able to detect changes in natural frequency when magnitude and phase cues were manipulated independently. This indicates the human ability to perform system identification of dynamic systems, while controlling them, regardless of the cue that is conveyed as well as human's versatility with regard to manual control situations. This might suggest why the driver adapts his steering wheel input frequency during the subjective closed loop evaluation.

In the Results section the study shows that the steering wheel torque is an important parameter for evaluating handling performance. In (Erdogan et al. (2011)), researchers explored the effects of parameters constituting a second order dynamic system on the rate of human motor adaptation while performing a rhythmic dynamic task. Results provided evidence that the rate of human motor adaptation is strongly related to the required effort to complete the task and this rate decreases as the effort to complete the task increases. This can suggest that there might be a trade-off on the usage of haptic feedback. The right level of haptic feedback can increase the perception of the task dynamics, hence affecting the performance. However, too much haptic feedback can negatively affect the tracking performance as result of an increase in the effort required to perform the task. This might provide insights on why the data analysis results shows a better correlation between the driver's subjective closed loop rating and the steering wheel torque related metrics rather than the steering wheel angle related metrics.

Another interesting result from the subjective closed loop data analysis and correlation, is the importance of the roll response for the understanding of the driver's subjective assessment. In this paper, in addition to vehicle roll response, the lateral and yaw vehicle responses have been analysed. The approach used was the same as this one for the roll response analysis. Time delays between the lateral (Ay CoG)/yaw (Yaw Rate) vehicle response and the steering wheel torque (SWT) input have been calculated at the frequency used by the driver during the subjective closed loop evaluation. Results show that a delayed roll response (Roll Angle) over the steering wheel torque input (SWT) is linked with a better coupling of the yaw and lateral vehicle responses (highlighted in green in Tab. 1).

This indicates a better handling performance and consequently a higher driver's subjective rating (highlighted in green Tab.1):

In (Tao et al. (2017)), a new hypothesis for the vehicle dynamics characteristics which could realize the performance is proposed, using the driver's steering operation mechanism analysis in closed-loop situation. In this paper, the delay of the roll angle response over the steering wheel input seems to be crucial to achieve a good coupling of the yaw and lateral vehicle responses, resulting in a better vehicle handling performance. This confirms our findings on the importance of the roll response for the subjective handling performance evaluation. In addition to that, the importance of the roll motions as subjective and objective

	time delays @ frequency chosen by the driver for the SINE SUBJECTIVE CLOSED LOOP			Subjective Closed Loop CLUSTER 1
Tire Construction	*Roll Angle - SWT*	*Yaw Rate - SWT*	*Ay CoG - SWT*	*HANDLING BEHAVIOR*
1	0.137	-0.108	-0.120	1
2	0.149	-0.097	-0.100	1
3	0.138	-0.096	-0.105	1
4	0.146	-0.105	-0.105	1
5	0.141	-0.108	-0.117	1
6	0.124	-0.103	-0.103	2
7	0.097	-0.104	-0.110	2
8	0.151	-0.099	-0.100	2
9	0.112	-0.109	-0.117	2
10	0.093	-0.124	-0.127	2
11	0.056	-0.131	-0.087	3
12	0.093	-0.143	-0.114	3
13	0.055	-0.143	-0.099	4
14	0.062	-0.140	-0.100	4
15	0.067	-0.145	-0.096	4
16	0.071	-0.159	-0.096	4
17	0.083	-0.147	-0.102	4

Table 1. Time delays between the main vehicle responses (roll angle, yaw rate, lateral acceleration) and the steering wheel torque calculated at the frequency chosen by the driver for the subjective closed loop evaluation

modifier is mentioned in (Blundell and Harty (2014)). Authors stated that the fact that during pure roll motion, the front axle is moving with a higher lateral velocity than the rear axle (because of the lower front anti-roll geometry), causes the front tires to experience an increased front slip angle compared to rear tires. When the roll motions are delayed over the yaw motions this is not happening and we found a higher increase for the rear tires' slip compared to the front tires' slip. The yaw and lateral motions coupling in response to a sinusoidal input have been studied and simulated with a bicycle model in (Minakawa (2016)). In this paper, it is stated that the delay of lateral acceleration relative to the yaw velocity in response to a sinusoidal steering wheel input is solely dependent of the side force characteristics of the non-steered axle (rear axle). This conclusion has been drawn already in (Pagliarecci and Zimmer (2018)) highlighting the importance of the rear cornering stiffness for a faster yaw response (rear slip gradient, RSG [°/g] = Load Rear Axle/ Cornering Stiffness Axle from bicycle model simulation).

It must be said that, when the handling behavior between the same vehicle equipped with different tire constructions, is quite similar in terms of tire Force & Moment features, this method become limited. Subjective differences in handling behavior might arise but the objective measurements are not able to detect them.

5. CONCLUSION

The analytical testing methodology and the data analysis proposed in this paper results to be efficient and statistically robust for the linear domain handling performance understanding. Usage of the methodology in the attempt to correlate objective measurements with driver's subjective rating provides objective metrics linked with the driver's subjective evaluation and it can gauge performance (handling behaviors classification). The methodology allows to define the relevant subjective items to be studied for the linear domain vehicle-tire handling performance characterization. In addition to that, the data analysis provides insights on the human-vehicle interaction.

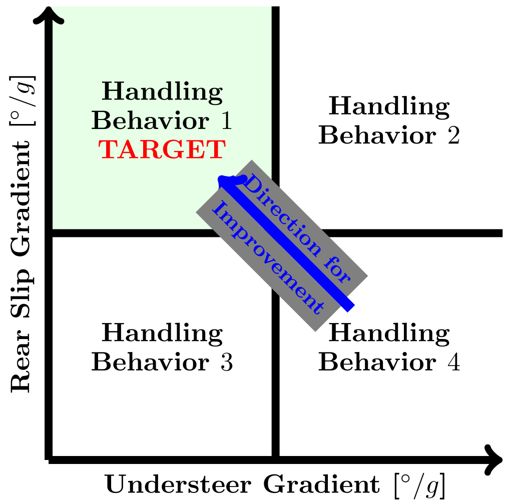

Fig. 12. Example of handling behaviors' classification based on Force & Moments macro indicators (tire cornering stiffness front/rear)

This paper indicates that investigations results in human motor adaptation in haptic virtual environments (Israr et al. (2009)) are applicable to the subjective assessment of handling performance. Information on driver's steering input control and regulation are deeply connected with the vehicle responses and, in this paper, it is possible to classify and merge a specific steering wheel input with a specific vehicle response and then with a specific vehicle-tire handling behaviour. The handling behavior classification based on the results of the PCA (section 2) proposed in this paper results to be useful to provide more reliable subjective evaluations of handing performance by reducing the assessment's complexity. The handling behaviour classification might be used during the initial phases of the development to provide the direction to the designers (Fig.12) and to quickly converge reducing the iterations. In addition to that, the importance of the steering wheel torque as the main input during the subjective closed loop evaluation has been emphasized. This finding, not new in the automotive field, can provide the next steps for the research related to the handling performance understanding.

REFERENCES

Ahad, N. and Syed-Yahaya, S.S. (2014). Sensitivity analysis of welch's t-test. volume 1605, 888–893. doi: 10.1063/1.4887707.

Altman, D., Machin, D., Bryant, T., and Gardner, M. (2013). *Statistics with Confidence: Confidence Intervals and Statistical Guidelines*. Wiley.

Badji, B., Fenaux, E., Bagdouri, M., and Miraoui, A. (2009). Nonlinear single track model analysis using volterra series approach. *Vehicle System Dynamics*, 47, 81–98.

Blundell, M. and Harty, D. (2014). *The Multibody Systems Approach to Vehicle Dynamics*. Elsevier.

Erdogan, A., Israr, A., O'Malley, M., and Patoglu, V. (2011). Rate of human motor adaptation under varying system dynamics. 167–172.

Gmez, G.L.G., Nybacka, M., Bakker, E., and Drugge, L. (2015). Findings from subjective evaluations and driver ratings of vehicle dynamics: steering and handling. *Vehicle System Dynamics*, 53(10), 1416–1438.

Israr, A., Kapson, H., Patoglu, V., and O'Malley, M. (2009). Effects of magnitude and phase cues on human motor adaptation. 344–349.

Jolliffe, I. and Springer-Verlag (2002). *Principal Component Analysis*. Springer Series in Statistics. Springer.

Kim, J. and Yoon, Y.S. (2015). Objectification of steering feel around straight-line driving for vehicle/tyre design. *Vehicle System Dynamics*, 53, 1–18.

Minakawa, M. (2016). The roles of front and rear cornering stiffness in vehicle directional dynamics. *SAE International Journal of Passenger Cars - Mechanical Systems*, 9.

Pacejka, H. (2006). *Tire and Vehicle Dynamics*.

Pagliarecci, N. and Zimmer, F. (2018). Linear single-track model vs handling behaviors. goodyear luxembourg. Technical report, Goodyear Luxembourg, Colmar-Berg.

Rajamani, R. (2006). *Vehicle Dynamics and Control*.

Tao, M., Sugimachi, T., Suda, Y., Kato, D., Shibata, K., and Li, J. (2017). A study on vehicle dynamics and driver model to improve driver's line traceability in cornering. volume 1.

Zimmer, F. (2019). Concept of typologies applied to vehicle handling. Technical report, Goodyear Luxembourg, Colmar-Berg.