DSC North America 2003 Proceedings, Dearborn, Michigan, October 8-10, 2003 (ISSN 1546-5071).

INFLUENCE OF STEERING WHEEL TORQUE FEEDBACK IN A DYNAMIC DRIVING SIMULATOR

D. Toffin [1,2], G. Reymond [1], A. Kemeny [1,2], J. Droulez [2]

[1] Renault - Technical Centre for Simulation, Renault Technocentre, 1 avenue du Golf, 78288 Guyancourt cedex, France. Email: (david.toffin, gilles.reymond, andras.kemeny)@renault.com

[2] Laboratoire de Physiologie de la Perception et de l'Action, CNRS - Collège de France, 11 place M. Berthelot, 75005 Paris, France. Email: (david.toffin, andras.kemeny, jacques.droulez)@college-de-france.fr

ABSTRACT

A preliminary study on the role of torque feedback in the steering wheel was conducted on the Clio dynamic driving simulator at RENAULT. An experiment comparing different torque feedback strategies was conducted to evaluate the potential of driving simulators in the study of future steer-by-wire systems.

The results indicate that drivers on the simulator can control their vehicles in curves with quite different torque feedback strategies, either linear or non-linear. However, zero torque or inverted torque feedback makes driving almost impossible. These observations confirm the essential role of coherent haptic information for driving real cars and simulators, and also suggest the existence of driver adaptation mechanisms in steering control.

INTRODUCTION

Automobile driving is often regarded as a visually-guided task, mainly due to its early description by Gibson (1). Subsequent works have identified the sources of visual information available to the driver related to vehicle control, such as time-to-contact (2), tangent point (3) and splay angle (4). However, the coupling between such variables and the motor actions applied to the vehicle commands is rarely straightforward, and require the driver to perform the sensory-motor control of a complex dynamic system.

Through their initial training and further practice, drivers acquire an internal model of the dynamic behavior of their vehicle, allowing them in particular to anticipate their future course in response to their actions of the steering wheel. The construction of this internal model is possible from visual information only, but is generally enhanced by the presence of haptic feedback on the system controls. Experiments on the manipulation of systems of *a priori* unknown dynamics show that the presence of haptic feedback helps significantly the operator to perform a visually-guided tracking task (5). In the case of vehicle steering, Bertollini and Hogan (6) showed that the drivers' preference for steering wheel torque feedback change with vehicle speed, which is in accordance with previous findings (7) showing that drivers prefer steering effort to increase with vehicle speed.

Drivers steer their vehicle by means of a steering system composed basically of: a wheel, a steering column, a Cardan joint, a rack-and-pinion, and steering tierods connected to the front wheels. The force appearing on the steering wheel is the resultant of the road contact forces applied to the tyres, and of the kinematic arrangement of the steering system. Additional power steering systems modify this resulting effort for enhanced driver comfort. Several technologies are commonly used: rack-and-pinion with variable gear ratio, hydraulic power steering servoed or not to vehicle speed, and electric power steering. Future steer-by-wire systems will allow a complete mechanical decoupling of the steering wheel from the driving wheels, allowing to generate steering force feedback levels at will. However, in all these systems, the steering force feedback is approximately proportional to the steering angle at a given vehicle speed, road adherence and at limited rates of turn. In the classic steering configurations, forces appearing on the tyres are mostly proportional to the vehicle lateral acceleration, and these forces are transmitted proportionnally to the steering wheel with minimal distortion at low steering angles (8).

Therefore, the steering wheel force feedback is carrying relevant information regarding the instantaneous dynamics of the vehicle. This information, related to speed and trajectory curvature, might be used by drivers to reinforce the visual information to perform their steering task. For instance, driving experiments on a real car and a driving simulator have shown that perceived lateral acceleration is a cue used by drivers to adjust their speed in curves (9). Yet the question remains to identify whether the steering wheel force feedback is actually used by drivers to adjust their internal model of the vehicle dynamics, or is only necessary for them to control the position of their steering wheel in a robust way. Indeed, experiments on the manual control of dynamic systems have shown that underlying neuromuscular mechanisms must somehow integrate a representation of the mechanical compliance of the corresponding limbs and actuators (10).

To test these two hypotheses, we designed a new driving experiment on the RENAULT dynamic driving simulator, capable of rendering different types of steering force feedback in the same driving task. Simulator experiments are a valuable means to analyze driver perception and behavior in a validated environment where individual driving variables can be manipulated independently and reliably (11). Results show a very wide range of adaptation of the drivers to the various steering wheel feedback configurations tested.

EXPERIMENTATION

Driving Simulator

The RENAULT dynamic driving simulator uses a actual Clio II cockpit with fully operational commands (steering wheel, pedals, gearshift, etc.) and animated dashboards dials. An electric force feedback system is coupled to the steering wheel to render the steering torque up to 8 N.m in the configuration used in the experiments, computed in real-time by the advanced in-house vehicle dynamics simulation software. A Rexroth-Hydraudyne 6-axes electric motion platform is used to produce accelerations up to 0.5 g within a limited motion envelope, therefore rendering part of the car dynamics in normal driving situations (12). The driver is fully immersed in the virtual scene, composed of a 150° wide frontal image and three back-projection screens for the rear-view mirrors. Real-time digital images are computed by a SGI ONYX2 workstation and by PC-based image generators. Six projectors display the road scene, three for the front view and three for the rear-view mirrors.

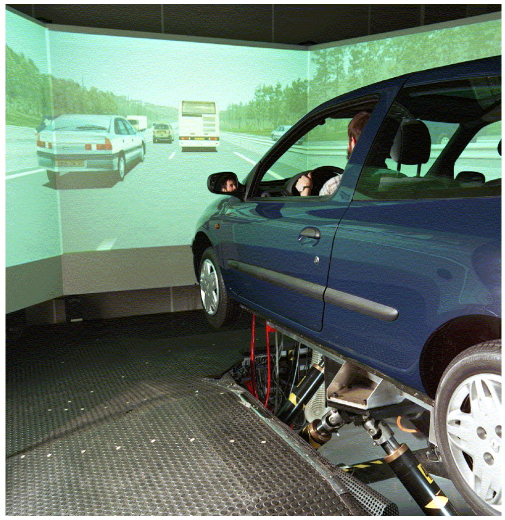

FIGURE 1: Driving Simulator Clio II

Protocol

Five participants from the RENAULT staff completed the experiment (mean age 29, average driving mileage 15.000 km/year). Among them, one participant (S3) was quite experienced in driving this simulator, the others had never driven on a simulator before.

Drivers were placed on a realistic virtual reproduction of one of RENAULT's proving grounds (Figure 2), and drove five laps in a row for each experiment. Instructions were given to drive at a constant speed (60 km/h), and to keep in the middle of the lane. Steering force feedback modifications were done by the simulator in a straight part of the road (cf. circle on Figure 2), so that the drivers would not be aware of it. During the simulation, several data were recorded at 20 Hz: steering wheel angle, vehicle position (x, y), lateral position inside the lane, vehicle speed, vehicle acceleration and local road curvature. Only the data recorded in the two first curves after the modification of steering feedback are presented in this study.

Experiment 1: Modification of steering wheel torque with two linear laws

During the three first laps, the steering feedback law K1 was used in the simulator, and was then changed to K2 before the 4^{th} lap. These two laws are linear with steering angle, and may be represented by a simple spring with stiffness 1.5 N.m/rad for K1 and 2.5 N.m/rad for K2 (Figure 3)

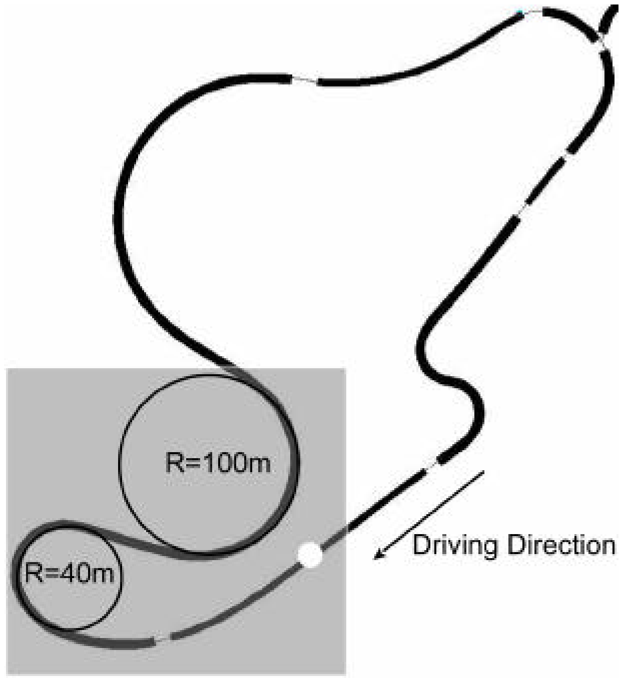

FIGURE 2: Test track used in the simulator experimentation. Circle represents the road position where the steering force feedback modifications are realized.

Experiment 2: Modification of steering wheel torque by using linear and no-linear law

The same protocol was used, the first law being again K1 as in Experiment 1, and the second being a non-linear law K3 with a parabolic profile saturated at 4 N.m (Figure 3).

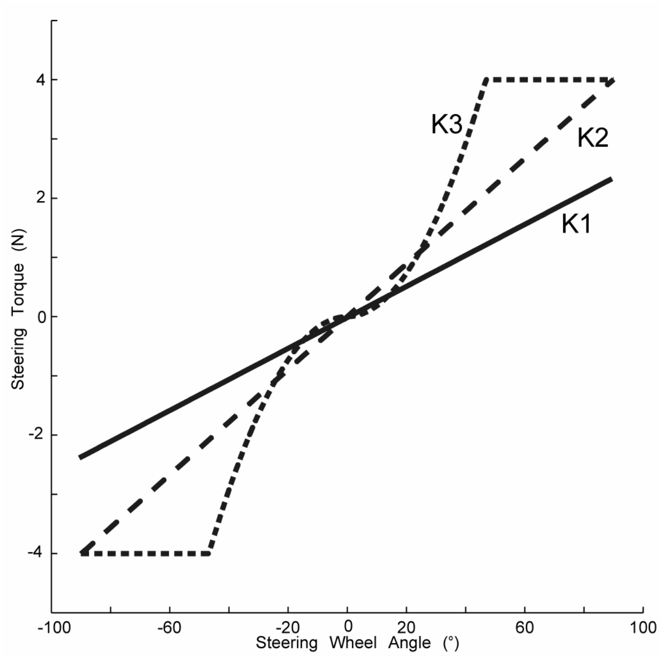

FIGURE 3: Different laws used in these two experiments, with K1 the standard law of steering wheel torque restitution.

Control experiment: Non-realistic force feedbacks

In this third experiment, two steering feedback laws were used: a null steering wheel torque K4 = 0; an inverted wheel torque K5 = -K1. Two drivers from the same group drove several laps on the same road with these steering configurations, which were not changed after the 3rd lap as in Experiments 1 and 2.

Analysis

For each driver and for each of the different recorded variables (steering wheel angle, lateral deviation, and lateral acceleration), a root mean square difference, defined by $RMS(x,y)=\sqrt{\frac{\sum_{i=1}^{n}(x_i-y_i)^2}{n}}$, was computed between the steering force feedback configurations K1 and K2, and between K1 and K3. This difference expresses the increase or decrease of steering variability in the different configurations, and reflects the level of adaptation of the driver to a modification of the simulated vehicle characteristics. A reference value was computed separately for K1 as the RMS difference between the first and second laps. This reference value expresses the basic variability of vehicle steering for each driver, as measured by the recorded variable considered.

The RMS obtained with the steering force feedback configurations K2 and K3 are compared to the reference RMS K1, and the difference is expressed in percentage (Tables 1-3). When this difference is *negative* or below a certain threshold, the steering variability has decreased, and the driver has adapted his steering strategy to the new steering force configuration. A 0.05 m/s² threshold is chosen for lateral acceleration, corresponding to a vestibular detection psychophysical threshold (13). For lateral deviation, a 0.1 m threshold is chosen arbitrarily, corresponding to a small (4%) error inside a 2.5 m wide lane. A threshold of 2° is chosen for steering angle, corresponding to a small (3.3%) error relative to the 60° steering angle in the sharpest turn (R=40 m). When the RMS difference is *positive* and above threshold, the steering variability has increased, and the steering performance has degraded in response to the change of steering configuration K2 or K3 compared to the reference condition K1.

The variables recorded during these experimentations have different meanings relative to the steering control task. The main performance criterion is the lateral deviation, corresponding directly to the driver task which is to keep in the middle of the lane. Lateral acceleration and steering angle have been also analyzed to study the modifications of steering control strategy.

Results

The results of lateral acceleration (Table 1) show that the drivers S1 (Figure 4) and S4 have not modified the vehicle control when the steering force feedback was modified to K2, and that for S2 the difference was below the 5% threshold. The result for driver S5 in this case is probably accidental, considering his correct adaptation with the K3 configuration. With the steering force feedback K3, drivers S2, S4 and S5 show a behavior also comparable to the steering force feedback K1.

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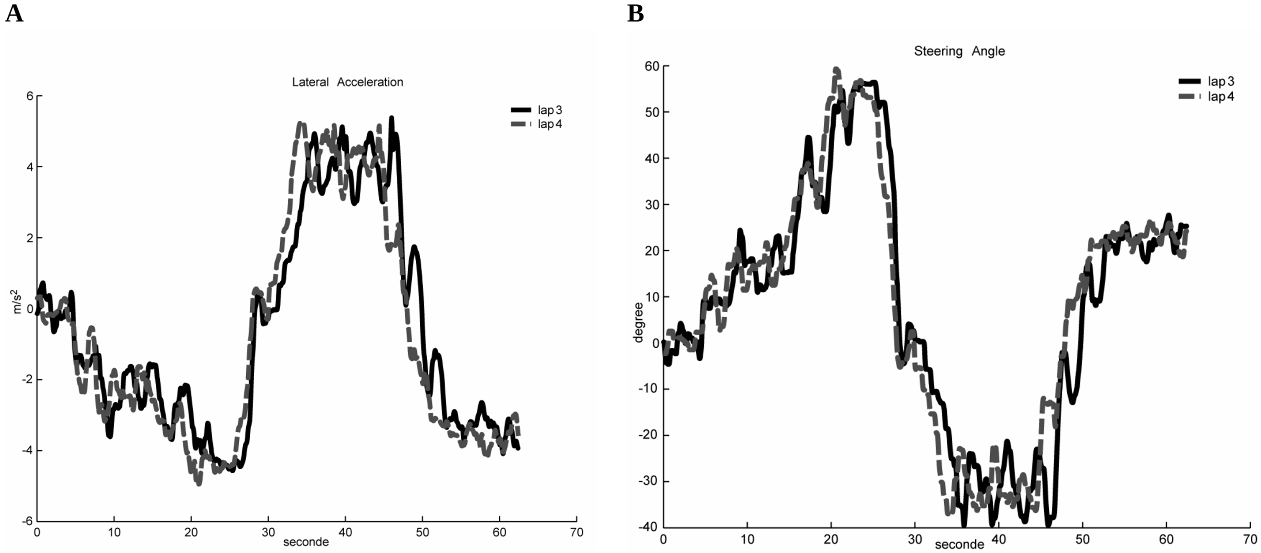

FIGURE 4: Example of representation of (A) lateral acceleration and (B) steering wheel angle. Data was recorded in two successive curves with steering force feedback configurations K1 in 3rd lap and K2 in 4th lap taken for one subject (S1).

TABLE 1: Lateral acceleration RMS analysis. Variations with reference RMS are indicated in percent, and RMS differences values below threshold (0.05 m/s²) are marked in gray.

Participants	Lateral acceleration RMS difference (m/s²)				
	Ref. K1	K2	% ref	K3	% ref
S1	1.15	1.08	-6.1%	1.35	+17.4%
S2	1.44	1.46	+1.4%	1.14	-20.8%
S3	0.71	0.84	+18.3%	1.33	+87.3%
S4	1.14	0.75	-34.2%	0.36	-68.4%
S5	0.35	0.71	+102.9%	0.34	-2.9%

The RMS results for lateral deviation (Table 2) show that all 5 drivers did not modify their steering control with the force feedback modification K2. For the steering force feedback K3, drivers S2, S4 and S5 show the same characteristic, where the difference in lateral deviation was below the 10 cm threshold.

TABLE 2: Lateral deviation RMS analysis. Variations with reference RMS are indicated in percent, and RMS differences values below threshold (0.1 m) are marked in gray.

Participants	Lateral deviation RMS difference (m)				
	Ref. K1	K2	% ref	K3	% ref
S1	0.45	0.39	-13.3%	0.78	+73.3%
S2	0.85	0.53	-37.6%	0.89	+4.7%
S3	0.71	0.49	-31.0%	0.91	+28.2%
S4	0.69	0.55	-20.3%	0.77	+11.6%
S5	0.41	0.40	-2.4%	0.37	-9.8%

The RMS results for steering angle (Table 3) show that drivers S1, S2, S3 and S4 have adapted their steering behavior to the force feedback K2. The result for driver S5 in this case is probably accidental, considering his correct adaptation with the K3 configuration and the similar observation in Table 1. For the law K3, a RMS decrease was observed for all 5 drivers.

TABLE 3: Steering wheel angle RMS analysis. Variations with reference RMS are indicated in percent, and RMS differences values below threshold (2°) are marked in gray.

Participants	Steering wheel angle RMS difference (°)				
	ref. K1	K2	% ref	K3	% ref
S1	10.22	8.46	-17.2%	11.80	+15.5%
S2	22.68	11.87	-47.7%	14.71	-35.1%
S3	18.04	9.88	-45.2%	10.52	-41.7%
S4	14.90	9.17	-38.5%	4.58	-69.3%
S5	5.41	11.02	+103.7%	5.04	-6.8%

In total, adaptation of steering behavior has occurred for all of the 5 drivers in both configurations, as measured by a significant decrease in steering variability indicated by at least one experimental variable.

Control experiment: For this experiment where particular steering wheel torque feedbacks were used (K4 = 0 and K5 = -K1), the observation is that all drivers obviously couldn't drive correctly, and stopped voluntarily the experiment because they could not control correctly the position on their vehicle in the middle of the lane.

DISCUSSION

The RMS study of the steering behavior with force feedback configurations K1, K2, K3 shows that the drivers did not modify significantly their vehicle control behavior in response to a modification of the steering feedback characteristics. However, significant modifications are observed for unusual steering feedback characteristics, including zero force feedback. Therefore, this experiment suggests that driver behavior adaptation can occur efficiently for a range of steering force feedback configurations, but this range is limited by certain acceptability limits.

The consistency of driving strategy observed in the different configurations tested, especially in terms of lateral acceleration, suggests strongly that the adaptation has not occurred at the vehicle dynamics model but more at the steering control level. Indeed, a modification at the vehicle dynamic level would have certainly led to a different driving behavior, at least in terms of dynamic safety limit management, by reference to the curve driving experiments carried out on the same simulator (9); this interpretation will be investigated further in future work.

In particular, a driver model is being developed to reproduce these effects, and to analyze by simulation experiments whether the adaptation can plausibly take place at a haptic control level or at a more cognitive level related to the internal model of the vehicle dynamics. This model will also allow to test other steering force feedback configurations, and to predict the corresponding driver adaptation limits, which can in return be validated using the driving simulator.

In addition, further experimental tests are expected to help analyze the relation between steering force feedback and lateral acceleration (or vehicle speed), since vehicle speed was imposed to the drivers in the specific protocol used here. This experimentation realized could be completed by real-world experiments, or by using different vehicle dynamics configurations in the driving simulator itself. Since the simultaneous perception of lateral acceleration in curves may also play an important role in driver steering behavior, these experiments will be carried out on the high-performance dynamic driving simulator developed in the framework of the European project ULTIMATE (Eureka #1493).

Nowadays, steering force feedback modifications are possible in real vehicles with computer-controlled electric power assist or steer-by-wire systems. Nevertheless, the development of these new systems requires the definition and testing of driver-optimal steering force feedback strategies. The experimental approach investigated here may contribute to identify critical haptic steering force information, or to design variable steering force feedback systems adapted to the driving tasks (maneuvering, curve driving, motorway driving, …), to improve driver comfort and safety.

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