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On the Assessment of Fitness to Drive: Steering and Brake Operative Forces

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ABSTRACT The Directive (EU) 2015/653 aimed at facilitating that the maximum force that any disabled driver could make on the vehicle's primary controls could be adjusted to their needs. The technical adjustment in the vehicle's design requires a measurement of the operational forces applied by the driver on the steering and brake controls, in order to determine its functional capacity during the execution of driving manoeuvres. The objective of this paper is to define the steering and braking operative forces used for driving current-market M1 motor vehicles for the fitness to drive assessment of drivers with physical disabilities. A total of 200 trials were performed with 17 different vehicles and 26 drivers. The results obtained help to define a new threshold's criteria for operative forces onto the steering and braking systems for adapting motor vehicles to disabled drivers. The main contribution of this paper consist on a new technical recommendations about the use of code 20.07 -braking- and 40.01 -steering- to be used in the fitness to drive assessment of driver with disabilities according to Directive (EU) 2015/653 requirements.

INDEX TERMS Braking forces, driving assessment, fitness to drive, steering operative forces.

I. INTRODUCTION

According to the World Health Organisation (WHO), 15% of the world population lives with some type of disability [1]. In the European Union (EU), it was estimated that there were around 70 million people aged 15 or over with some type of disability (17.6% of the population) [2]. Based on the projections, it was estimated that this value could be increased to 120 million in 2020 [3].

The difficulties of many people with disabilities, including the elderly, to access public transport services, force them to choose driving vehicles as the only way to ensure their mobility conditions [4], [5]. This fact obliges them to obtain or renew their driving license when they are subjected to a disability problem, or loss of their physical abilities derived from an illness or accident.

Directive 2006/126/EC of the European Parliament and of the council [6], amended in April 2015 by a new Commission Directive (EU) 2015/653 [7], represent actually the EU reference regulation for obtaining or renewing a driving license. According to that, a driver's license can only be granted to those who have passed a fitness-to-drive assessment, driving ability and behaviour tests in addition to comply with the medical standards established in their Annexes II and III. A list of harmonised community codes and sub-codes was first published in Annex I of Directive 2006/126/EC, and later adapted and updated in Directive 2015/653. These codes are related to the restrictions, limitations or adaptations that must be adopted by a certain driver (disabled, elderly, novice…) and must also be incorporated into their driver license. These codes are original from EU legislation as there are not similar ones to be used in other equivalent standards from developed countries as USA, Canada or Australia.

The aim of the update in [7] was to facilitate that the maximum force that a driver can exert on the vehicle's primary controls (steering, acceleration and braking systems) can be adjusted to their needs. So, it takes into account the state of the art in terms of technological developments in the design

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of both motor vehicles and control adaptations for vehicles. This approach tries to help drivers to choose the most suitable vehicle for their driving abilities. Specifically, the update in [7] eliminated obsolete codes, modified other ones, and introduced new European codes related to:

- Code 20.07 – Brake with a maximum operation force.
- Code 40.01 – Steering with a maximum operation force.

The introduction of this adjustment in the vehicle's design requires a measurement of the maximum operational forces applied by the drivers onto the steering and brake controls with their upper and lower limb, in order to determine if its functional capacity is enough for driving a motor vehicle during the execution of driving manoeuvres. These operational forces measurement should be performed during the physical assessment prior to in-car on-road fitness-to-drive assessment [4], [8]–[10].

According to CIECA Fit to Drive (FtD) topical group, the fitness-to-drive assessment "*is the state of having adequate physical, visual and cognitive function, and no medical (including psychological and neuro-psychological) or behaviour contraindication to driving*" [11]. Some works have dealt with the FtD problem from different points of view [12]–[14] However, although EU regulations explicitly describe the number and type of assessments that must be carried out to obtain a driver's license, the reality shows that there are diverse models of medical fitness-to-drive and driving ability assessment for people with disabilities, not only in Europe, but also in the rest of the world [11].

A. EU MODELS FOR FITNESS-TO-DRIVE ASSESSMENT

Differences between the EU models for FtD assessments were evidenced by the study developed by [15], later corroborated during the development of the CONSENSUS project [16]. The CONSENSUS project results showed that, in the EU context, the responsibility for carrying out the medical and practical evaluation of the driver with disabilities depends on each EU member state legislation [17]. The analysis concluded that the medical evaluation of the applicant's FtD could be done, either by a general practitioner, a centre specialised in driver assessment, or multidisciplinary commissions with different professionals involved -physical practitioners, transport or traffic administration, physiotherapists or rehabilitation specialists-.

The results obtained in CONSENSUS were later supported by the CONSOL project, developed to verify the application of the 3rd directive [6] on the driving license in 27 EU countries [18]. The CONSOL project results demonstrates the heterogeneity of the FtD, with general practitioners predominant among the professionals in charge of carrying out the assessment, showing that the methodology and evaluation tools used in each country are neither homogeneous nor standardised. A report recently published by CIECA [11] shows again that, nowadays, several inconsistencies still exist in different areas related to the FtD process across Europe as: on-road driving vehicles adapted or not, private or public off-road facilities, availability of driving static rigs, funding, assessment protocols, experience of professionals involved in the driver assessment, etc.

So the introduction of the new EU 20.07 and 40.01 codes in [7], to define the maximum force that the driver can exert on the primary controls during driving manoeuvres, has not simplified or resolved the problem, but its implementation has generated additional issues:

a) Firstly, the need to use a tool for measuring the maximum operational forces made by the driver onto the steering and brake pedal controls.
b) Secondly, the knowledge of the strength thresholds on which to compare the acquired measurements; such reference values must be specific to the type of vehicle on which they are to be compared, to determine the need to install an external assistance system or not on vehicle primary controls.

In case (a), an experimental tool is needed to assess the driver with disabilities to estimate the suitability on the use of technical aids to adapt a specific vehicle. In [4], [9], [10], [19]–[21] different methods of FtD and driving ability assessment to drivers with disabilities are described, but this topic is out of the scope of this paper.

In case (b), the lack of information on typical values of operative forces of an up-to-date motor vehicle, is revealed. The maximum efforts transmitted to the primary controls to get to drive in conditions of comfort and safety are today one of the most important factors to design the vehicle's systems and components thereof. The maximum operational forces depend not only on the type of driver but also on the conditions in which they have to be applied (instantly, prolonged, intermittent, etc.) Currently, these forces are defined in their maximum values by different regulations that, explicitly, determine the values that must be applied in the type approval procedure.

B. LEGAL FRAMEWORK IN THE TYPE APPROVAL PROCEDURE RELATED TO OPERATIONAL FORCES IN VEHICLE's PRIMARY CONTROLS

Regulation UN/ECE R79 [22] determines the technical requirements for the steering system M1 vehicle's type approval procedure. This regulation is applied to steering systems that include an effective mechanical link between the steering control (steering wheel) and the wheels to determine the trajectory of the vehicle, and advanced steering systems with driver assistance. According with this regulation [23], the maximum operational force allowed on the steering control is 150 N in case of intact steering equipment applied on the periphery of the steering wheel to ensure a turn with a radius of 12 metres for 4 seconds at a speed of 10 km/h; whereas in case of steering equipment with a failure, this force steps up to 300 N to ensure a turn with a radius of 20 metres for 4 seconds at a speed of 20 km/h.

On the other hand, UN/ECE R13-H [24] determines the M1 vehicles type-approval requirements regarding the braking systems. The braking equipment to be installed in a motor vehicle must be designed, manufactured and installed so that, under normal conditions of use, it can stop the vehicle in a controlled, stable and safe way, in the shortest possible distance, regardless of the conditions of vibration to which it may be subjected. The type approval procedure states that with an M1 vehicle the mean deceleration must not be lower than 5.8 m/s^2 and the maximum operative force onto the brake pedal must be equal or lower than 500 N. Note that in practice, currently all vehicles have ABS systems installed, and therefore, the efforts applied to the pedals are lesser than the maximum required in the type approval braking test.

However, the efforts required for the type-approval procedures do not represent the values usually applied by drivers in current market motor vehicles. Aspects such as comfort and safety related to the design of the primary controls are considered by the original equipment manufacturers (OEM), as factors on which a commercial confidentiality have to be maintained to ensure a niche market and to establish a differential added-value with respect to its competitors. Therefore, this type of data has remained opaque and has not been disclosed to the scientific community.

Given that, to carry out a profitable FtD assessment of a person with or without a physical disability it is necessary to know the real operational forces to be transmitted to the vehicle primary controls.

C. OPERATIONAL FORCES IN VEHICLE's PRIMARY CONTROLS

1) BRAKING OPERATIVE FORCES

There have been few research works in the scientific literature presenting results considering vehicle's operative forces on primary controls with naturalistic driving. One of the first studies developed in this area is conducted by Kember [25]. This work tries to evaluate the range of forces exerted by drivers with physical disabilities on the primary controls of different types of vehicles. Among the test batteries developed, a test was carried out to measure the operational forces exerted on 5 control adaptations in a typical vehicle without ABS. The results showed significant differences between the forces applied to the different types of control adaptations which, in the case of braking, reached minimum and maximum values of 266 N and 362 N respectively. This test was reproduced measuring the forces applied directly on the pedal brake. The results in this second case showed average forces on the pedal that ranged between 256 and 540 N, with deceleration varying between 5.42 and 6.98 m/s^2.

Horberry and Inwood [4] determine that the average braking efforts on a vehicle with ABS are around 140 N, although some models may need 180-340 N to perform an emergency stop. They establish that a driver may need an assisted servo brake system if they cannot perform a braking force of 90-140 N. Some vehicle manufacturers consulted by them determine that, on average, the braking forces needed to stop a vehicle are below a maximum force of 90 N, and in the case of emergency braking can reach 340-370 N in vehicles without ABS, and lower values for vehicles with ABS (currently all existing).

The authors of [26] have developed a research project sponsored by the Spanish Traffic Administration (DGT) and FIAT Spain SA company, in which the operational forces applied onto the controls of a single vehicle are measured during different manoeuvres representative of normal driving -steering wheel rotation at parking and a closed-circuit circulation-. The study involves 24 subjects distributed by age, gender and anthropometric measures. Within the testing battery, a sudden braking test of a vehicle equipped with ABS travelling at 50 km/h is performed. The average force on the brake pedal is 240 N, and its minimum value 111 N.

2) STEERING OPERATIVE FORCES

Along the last decades OEM have made a great effort in the development of different steering assistance systems to improve safety and comfort conditions when driving vehicles [27]. The introduction of electronics in automobile control systems has allowed the evolution from the old mechanical steering systems, through the hydraulic power assistance systems (HPAS) to the current electronic power assistance systems (EPS) [28]. This technological evolution has allowed a substantial reduction in the efforts applied to the steering wheel when driving a car [29].

One of the first works is carried out by Pettigrew [30], whose study is based on the measurement of the forces applied onto the steering wheel of three different vehicles subjected to different static and dynamic road tests. The results obtained for vehicles without power steering show that the maximum torque required to operate the steering system in stationary conditions is 31 Nm, while when the vehicle is in motion (at a speed of 10 km/h), the required torque is reduced to a minimum of 12 Nm. In emergency situations, these maximum values reach a range of 30-40 Nm.

Kember developed also a series of studies in [25] to obtain the necessary force in driving 5 identical vehicles without power steering, equipped with the same control adaptations and driven by the same drivers to avoid differences in driving styles. The results show that the average torque for turning the steering wheel in a parking manoeuvre with the vehicle in motion varies between 4.6 to 6.7 Nm, while with the vehicle stationary the average torque varies between 11.0 to 14.4 Nm.

The mechanical steering (MS) system has been used by older cars, and consists on a rack and pinion system or a recirculating ball steering activated by the steering wheel turning. In this system the operative steering force is produced exclusively by the driver and is the one that needs more strength [31], [32].

With the increase of car weight the MS has been progressively replaced by hydraulically assisted steering systems since 1950s. The hydraulic power steering (HPS) uses the rack as hydraulic piston, actuated by a hydraulic pump connected to the engine by a belt. So, this solution represent a servo system actuating parallel to a pure MS where the operating force is produced by the muscular energy of the driver and by an energy source [28]. Since 1990s, a further development of this system was the electrohydraulic power steering (EHPS). The EHPS device substitutes the action belt actuating over the hydraulic pump by an electric motor powered by the vehicle battery to facilitate easy steering in low-speed manoeuvres, as e.g. parking [33].

In parallel, new assistance devices operated by electrical powered systems (EPS) were introduced in the market since 1988, which are activated only as a power-on demand system. Generally, in the EPS the supporting energy is provided by an electric motor powered by the vehicle's electrical system. Actually there are different EPS devices distributed in the market, designed according to the vehicles' conditions and manufacturers' technological philosophy [27]. Depending on the location of the electric motor, there are different EPS typologies. The first design, in which the electric motor is fitted to the steering column, was introduced in the market in the late eighties for sub-compact, compact and mid-size cars. This was so-called EPS:Column (EPSc) [34]. When the electric motor is fitted to the pinion-drive, called EPS:Pinion (EPSp), the powered system can apply slightly higher steering power than EPSc [35]. Since 2002, the EPSp has a second pinion, called EPS:Dual Pinion (EPSdp), which can obtain an additional 10-15% power with respect to the EPSc and EPSp systems. Both EPSp and EPSdp are applied to mid-size and upper-mid-size cars. Finally, since 2007 the newest EPS has been introduced in the market where the steering forces are applied directly by the electric motor to the rack combining a ball screw and a timing belt gearbox. This system was called EPS:Axle Parallel (EPSapa), and has a variant where the motor has a hollow shaft that is mounted concentrically around the rack, called EPS:Rack Concentric (EPSrc) [34]. These last technologies have been applied for upper-mid-size and upper class cars, luxury and off-road vehicles.

A new and completely different approach in the automotive industry is the x-by-wire technology, which uses electrical or electromechanical systems for performing vehicle functions traditionally achieved by mechanical linkages [36]. This technology replaces the traditional mechanical control systems with electronic control systems using electromechanical actuators and human-machine interfaces such as pedal and steering feel emulators [37]. Components such as the steering column, intermediate shafts, pumps, hoses, belts, coolers and vacuum servos and master cylinders are eliminated from the vehicle. There are adaptations for tetraplegics where, in some cases, the original steering wheel is eliminated and an additional joystick-based system is added, which is an example of x-by-wire application for disabled people. However, it should be mentioned that x-by-wire steering systems are out of the scope of this work, because we focused on vehicles with conventional technology. That is, vehicles with steering wheel and pedals directly attached to the kinematic chain, which takes the effort from these controls and brings it to the wheels through a MS combined with steering and brake advanced assistance systems.

From the perspective of OEM, the torque applied to the steering wheel represents one of the aspects that most influences vehicle handling and drive-ability [38]. The trend in the design of these systems is to reduce torques on the steering by increasingly applying external assistance to the steering system as the vehicle lateral acceleration increases [28], [32]. Some typical values for sport cars with a lateral acceleration of 0.3g (2.94 m/s^2) show steering wheel torque ranges from 4 to 5.5 Nm. In case of extreme manoeuvres with 0.8g (7.84 m/s^2) lateral deceleration these torques increases to a range of 4.5 to 6 Nm [39]. The longitudinal and lateral accelerations in daily driving situations (urban, highway or country side) depend on driver, vehicle and road conditions. Generally-speaking this standard driving situations have a lateral acceleration falling under 0.2g (1.96 m/s^2), and the steering wheel torque level, depending on the assistance system applied, ranges from 2.5 to 6.0 Nm in current market standard cars [40].

D. OBJECTIVES

Considering the issues mentioned above, the aim of this paper is to define the steering and braking operative forces in driving, to be used in the physical assessment that takes place prior to in-car on-road driving assessment of drivers with physical disabilities during the FtD assessment. The definition of the driving strength thresholds obtained in this study is being established considering the fulfilment of several conditions:

- The operational forces thresholds have to be defined according to current market vehicles, taking into account the up-to-date different driving assistance technologies.
- The operational forces have to be representative of driving motor vehicle's manoeuvres (sharp and circle curves, zig-zag, sudden braking, etc.), that is, they must be obtained with the vehicle in motion in road tests.
- The operational forces have to be representative of people without disabilities, since these are thresholds that will be compared to the motor skills of drivers with physical disabilities.

Consequently, the following two hypotheses must be demonstrated in this study:

- Do the following vehicle characteristics significantly affect to the steering wheel or brake pedal operative forces?: Antiquity, segment, weight, length, power steering system.
- Do the following population characteristics significantly affect to the steering wheel or brake pedal operative forces?: Age, gender, years of driving experience.

II. MATERIAL AND METHODS

A. SCOPE AND EXCLUSIONS

This study includes M1 vehicles, referred to as motor vehicles with no more than eight seats in addition to the driver designed and manufactured for the transportation of passengers, as established in Directive 2007/46/CE [23]. Vehicles of M2, M3, N and O categories, as well as non-four-wheel vehicles were excluded. Only M1 motor vehicles registered after 1990 were included, in order to avoid problems related to the deterioration thereto.

B. DRIVING TESTS

This study is focused on measuring the maximum operational forces and movements applied by the drivers while driving the vehicle, in such situations that could represent the maximum range of operative forces. Therefore, we choose, based on economic and functional purposes, vehicle driving tests and driver actions to be as similar to the ones used in the type approval process of M1 vehicles [23]. The objective of the driving tests was the acquisition of vehicle characteristics (objective parameters) from standardised vehicle manoeuvres [40]. The testing methodology was designed as a closed-loop manoeuvre where the driver takes the control of the vehicle, acting onto the primary controls and responding itself to fulfil the driving task, as e.g. a lane change or constant-radius cornering [31].

That is, the type of manoeuvres designed during the testing battery were defined as:

- **Slalom test**: generates data to assess the steering-feel and steering precision around a central position where the vehicle drives around corners changing direction lines (left and right turns) at 30 km/h between 5 cones positioned in straight line with 15 meters of distance each, being the first cone at a distance of 50 meters from the starting line. This test is focused mainly in the steering forces based on UN/ECE R79 [22], but it is also inspired by ISO 13674-1 [41] and ISO 8725 [42] standards.
- **Braking test**: in a straight line section of 120 m long the vehicle reaches and maintains a steady-state velocity of 50 km/h. When the front of the vehicle reaches the braking point, the brake pedal is fully pressed until the vehicle is stopped. This test focuses on forces in the brake pedal based on UN/ECE R13-H [24].
- **Step Input test**: has the aim to characterise the vehicle's transition from a straight trajectory into a constant-radius turning, as representing a roundabout. The vehicle accelerates in a straight line and it is steered to follow a cornering path where it performs three laps to a roundabout of 10 meters of radius with a constant speed of 30 km/h, first in counterclockwise direction and then in clockwise direction. This test is focused in the steering forces based on UN/ECE R79 [22] and it is also inspired by the ISO 7401 standard [43].

Table 1 shows a graphical description of testing characteristics and variables stored during the trials. A total of 200 trials were performed, 50 for each type of test (slalom, brake, step input test: counterclockwise and clockwise roundabout). Two to five trials were performed with each vehicle, each trial with a different driver. Each driver performed one to eight trials with different vehicles depending on availability on tests' day. Testing was developed at the Ricardo Tormo Circuit facilities (Cheste-Valencia, Spain). All the trials followed a close-circuit sequence, beginning with the slalom test, continuing with the braking test and, lastly, developing the step input test in both counterclockwise and clockwise direction, as it is described in Figure 1.

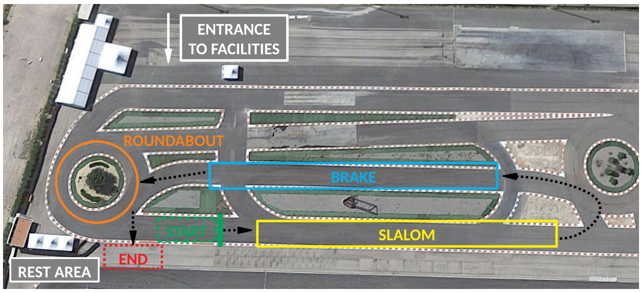


FIGURE 1. Closed circuit testing sequence.

C. VEHICLES

In the present study, 17 different vehicles took part. Each vehicle performed 2 to 5 tests (slalom, braking, step input tests), each one with a different driver. Table 2 presents the technical characteristics of the vehicle involved in the testing trials. The main vehicle features studied were: power steering type, vehicle segment, weight, length and antiquity. Vehicle segment is a classification based on common characteristics such as engine power, dimensions and other technical features. There are segments, going from A to F (from smallest to largest) plus other categories like "all-terrain" or "van" [44]. For our study, six vehicles belong to segment B, nine vehicles of segment C, one of segment E and another one of segment "van". All the vehicles tested were equipped with ABS braking system.

Regarding the state of the art in steering systems technology development [27], [29], [32], three categories of assistance systems were considered in the vehicles analysed in the study:

- Type 1: mechanical steering (MS). Only one vehicle was tested with this steering technology.
- Type 2: in this category we combine hydraulic power steering systems (HPS) and electronic power steering with EPSc and EPSp technologies. Five vehicles were equipped with HPS technology, one vehicle had the EPSc type, and four EPSp vehicles were tested.
- Type 3: this category includes the electrohydraulic power-assisted steering (EHPS) and electronic power steering-EPSdp generation. Five vehicles with EHPS were tested and only one vehicle included EPSdp.

To prove the initial hypotheses the vehicle antiquity was divided into three categories, whereas vehicle's weight and length were divided in two groups, rounding the mean value for each case.

- Antiquity: 7 vehicles with less than 10 years, 8 vehicles between 10 (included) to 19 years, and 2 vehicles with 20 years or more. The mean registration year for the

TABLE 1. Driving tests scheme.

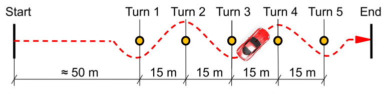
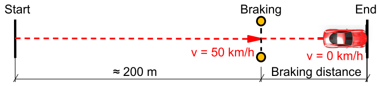
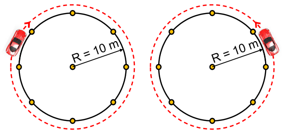
Driving Test	Graphical description	Variables measured
Slalom		- GPS position. - Linear velocity/acceleration X, Y. - Angular velocity/acceleration Z. - Brake pedal force. - Steering torque.
Braking		- GPS position. - Linear velocity/acceleration X, Y. - Brake pedal force. - Maximum Brake Force.
Step Input		- GPS position. - Linear/angular velocity X, Y. - Linear/angular acceleration Z. - Brake pedal force. - Steering torque.

TABLE 2. Technical characteristics of vehicles involved in the testing trials.

#	Vehicle Model	Year	Segment	Weight [kg]	Length [mm]	Fuel	Engine capacity [cm^3]	Power [HP]	Power Steering	Braking System
1	VW Golf mk2 gti 8V	1991	B	1015	3985	Gasoline	1781	107	Mechanical	Hydraulic+ABS
2	VW Polo Bluemotion tdi 1.4	2016	C	1151	3972	Gasoline	1422	90	Electric	Hydraulic+ABS
3	Audi A6	2002	E	1520	4796	Gasoline	2496	155	Hydraulic	Hydraulic+ABS
4	Opel Corsa C 1.3 cdti	2005	B	1135	3839	Diesel	1248	69	Electric	Hydraulic+ABS
5	Toyota Auris hybrid	2016	C	1370	4330	Hybrid (Gasoline)	1798	136	Electric	Hydraulic+ABS
6	Dacia Logan essential 0.9 TCE GLP	2018	C	1570	4358	Gasoline	898	90	Hydraulic	Hydraulic+ABS
7	Citroen C4 coupé	2006	C	1257	4247	Gasoline	1361	88	Electrohydraulic	Hydraulic+ABS
8	Citroen C4	2006	C	1257	4260	Gasoline	1360	80	Electrohydraulic	Hydraulic+ABS
9	Peugeot 2008	2015	B	1350	4159	Diesel	1560	120	Electric	Hydraulic+ABS
10	Honda Civic eg 4	1995	C	950	4080	Gasoline	1493	90	Hydraulic	Hydraulic+ABS
11	VW Tiguan	2018	C	1585	4490	Gasoline	1395	150	Electric	Hydraulic+ABS
12	Skoda Fabia	2002	B	1065	3960	Gasoline	1397	60	Electrohydraulic	Hydraulic+ABS
13	Seat Ibiza	2005	B	1125	3953	Diesel	1896	63	Hydraulic	Hydraulic+ABS
14	Renault Clio	2014	B	1165	4077	Gasoline	1197	120	Electric	Hydraulic+ABS
15	Ford Focus	2009	C	1335	4464	Diesel	1560	90	Hydraulic	Hydraulic+ABS
16	Citroen Jumpy Atlante	2010	Van	1896	4805	Diesel	1997	120	Electrohydraulic	Hydraulic+ABS
17	Toyota Auris	2007	C	1305	4220	Gasoline	1598	122	Electrohydraulic	Hydraulic+ABS
	AVERAGE	2008	-	1297.1	4235.0	-	1556.3	102.9	-	-
	STD DEV	7.8	-	240.7	282.9	-	363.2	28.8	-	-
	MEDIAN	2007	-	1257	4220	-	1493	90	-	-

studied vehicles was 2008, that is 13 years of antiquity. The average age of the vehicle stock in Spain was 12.4 years (for vehicles registered after 1990) [45], which means that the vehicles used in the trials were similar to actual market.

- Weight: 12 vehicles with less than 1300 kg and 5 vehicles with equal or more than 1300 kg; the mean weight value calculated from all vehicles was 1297 kg.
- Length: 5 vehicles with less than 4200 mm and 12 vehicles with equal or more than 4200 mm; the mean length value calculated for all vehicles was 4235 mm. 4200 mm is also the usual measure of segment B vehicles [44], therefore vehicles shorter than 4200 mm represent segments A and B, and vehicles with length larger than 4200 mm represent segments C, D, E and "van".

D. DRIVERS

In this study a total of 26 volunteers participated. The drivers were 20 to 65 years old with a minimum of 2 years of driving experience, excluding novice drivers. Each one of them performed the tests between 1 to 8 times with different vehicles. For the study of the initial hypotheses, population was divided in two groups considering age. One group of people with less than 30 years (17) and the other one with 30 years or more (9). Regarding driving experience, population was also divided in two groups, one with less than 7 years of experience (13) and the other with 7 or more years of experience (13). Finally, participants were split by gender, having one group with 6 women and another with 20 men. All the participating drivers were previously informed of the scope and objectives of the study, and signed a document of consent and confidentiality approved by the Ethics Committee of the Universitat Politècnica de València (ref. P5-18-06-19).

E. DATA ACQUISITION SYSTEM

Figure 2 shows the data acquisition system (DAQ) used to measure vehicle's dynamics and the operative forces applied during test trials. The DAQ was designed and validated in [46], [47], and it is composed by the following sensors:

- A steering wheel torque sensor Mecmesin ST60, which measures the force F_S at the steering wheel's perimeter,

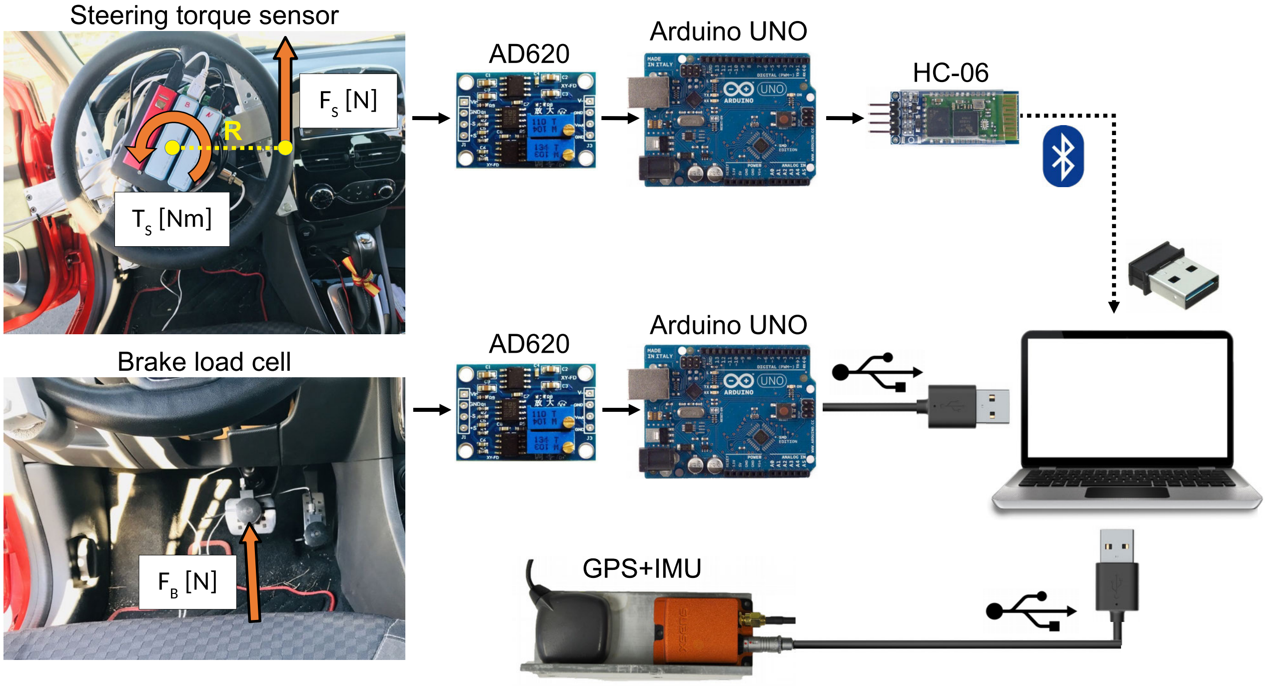


FIGURE 2. Data acquisition system used in the trials, including steering wheel torque sensor (top), brake pedal load cell (center) and GPS+IMU sensors (bottom).

at a distance $R = 0.17$ m from the steering column where the torque T_S is applied (see top left corner in Figure 2). This sensor can register a maximum torque value of $T_S^{max} = 60$ Nm with a 0.02 Nm resolution and 0.5% full scale accuracy. The steering sensor is attached to an external steering wheel device, which uses a worm screw to make it adaptable to a wide range of steering wheels sizes. Inside the assembly, an Arduino UNO board with Bluetooth HC-06 wireless transceiver was installed to send data to the logger at a rate of 100 Hz.

- A load cell Honeywell 3663-20 attached to the brake pedal to measure force F_B applied perpendicular to the pad (see bottom left corner in Figure 2). The brake pedal load cell has a full scale of 890 N and an electronic circuit with a Wheatstone bridge with a resistance of 298 kΩ at 25°C. It is wired to an AD620 amplifier, which is connected to an Arduino UNO board to send information at a rate of 100 Hz to the computer via an USB port connection.
- An Inertial Measurement Unit (IMU) with a Global Positioning System (GPS) Xsens MTi-G-710, as shown at the bottom center of Figure 2. The IMU can measure orientation, angular velocity and linear acceleration, but combined with the GPS receiver the global position can also be measured, as well as the linear velocity. The GPS+IMU devices were used to measure position, velocity and acceleration, logging data at a sampling rate of 100 Hz. The IMU is equipped with a three-axis magnetometer (full range ±7.85 rad/s, bias error 0.0035 rad/s), three-axis accelerometer (full range ± 200 m/s^2, bias error 0.05 m/s^2). The dynamic accuracy of the orientation is 0.005 rad (pitch/roll) and 0.014 rad (yaw). The GPS has an horizontal accuracy of 1 m (Cartesian coordinates x/y) and 2 m for vertical (z coordinate). The IMU was carefully placed in a horizontal plane inside the cabin, centered on top of the rear axle to be aligned with the vehicle's instantaneous center of rotation.

F. TRIALS PROCEDURE

In order to ensure repeatability, the DAQ was calibrated before each set of trials, i.e., for each car and driver. A compact force gauge model Mecmesin CFG+ 500 (full scale of 500 N) was used as reference caliber for the steering wheel and pedal load cell sensors. For more details about the calibration procedure read [46].

All the tests were carried out with the vehicle loaded with a driver and an accompanying operator in charge of mounting and activating the DAQ. A reconnaissance tour of the entire test track was carried out the first time a driver performed the test, to ensure they could drive under the expected conditions. Drivers were asked to position the vehicle in the starting line before conducting the tests, which were carried out always in the same order: Slalom, Braking, Step input clockwise and counterclockwise. When a sensor transmission failure occurred during the execution of a driving test, it was repeated under the same initial conditions.

G. SIGNAL TREATMENT

The collected data was processed to erase distortions, offsets and errors that had appeared during the recording. From the data collected the following metrics were calculated according to statements in [48]: means, typical deviations, maximum and minimum values and 85th percentile (which represents the 85% of the values found below this in a normal distribution). Firstly, the percentiles 85 (P85) of the operative forces in the steering wheel were analysed using graphics with which force thresholds could be determined. Brake pedal forces were calculated in their maximum values for each trial. Secondly, a statistical analysis was performed to find out the characteristics of vehicles and population that significantly affected to the primary control efforts in driving.

To accept the data, some conditions had to be met. Firstly, the records of a trial ought to have no more than a 10% of missing or erroneous values. Moreover, a speed range was defined to accept the data of a trial. This was based on a calculation made considering that the vehicle's odometer were allowed to show, as maximum, a 10% of increase of the real speed plus 6 km/h, as per UN ECE Regulation 39 [49]. Therefore, if the odometer marked the target speed of 30 km/h for tests involving steering forces, or 50 km/h for testing brake forces, the real speed accepted had to be a minimum value of approximately 22 km/h and 40 km/h, respectively.

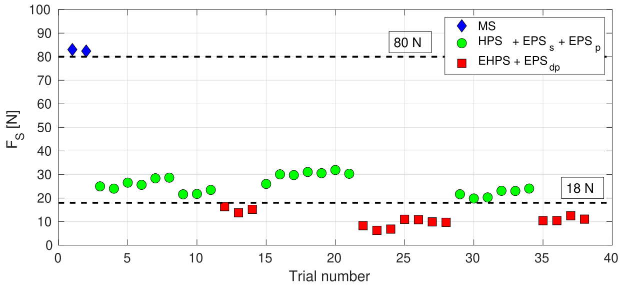
For the lower limit, 2 km/h from these speeds was allowed, having a 20 km/h lower limit for the slalom and step input trials and a lower limit of 38 km/h for braking trials. The higher limit is not considered to be so critical for the validity of the results and a speed 10 km/h higher than the target speed was considered acceptable. So, in the slalom and step input tests, the vehicle speed must be inside the acceptance range during the whole trial [20 km/h, 40 km/h], while in the braking trial the vehicle speed needs to be inside the acceptance range [38 km/h, 60 km/h].

H. STATISTICAL ANALYSIS

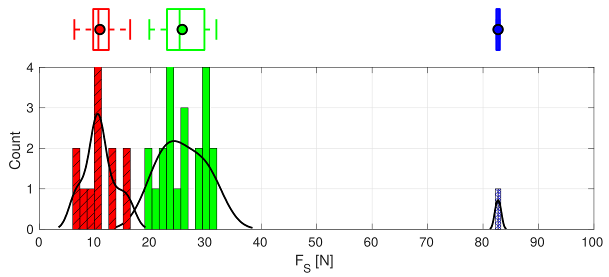
Once calculated the P85 for the steering and maximum values for braking forces, the initially defined hypotheses were tried to be proved. Each category from both vehicles and drivers were split in two or more population in order to perform an ANOVA test and compare them to see if a significant difference was obtained [50], [51].

ANOVA assumed in the null hypothesis that the means of the populations being compared were the same. This was contrasted with the alternative hypothesis that there was no relationship between the means of the analysed population. The population comparison was considered statistically significant when the populations unlikely comply with the null hypothesis according to an established threshold of probability, the significance level (α). For this study, the commonly used significance level of $\alpha = 5\%$ is considered. This means that bellow this threshold, the null hypothesis is rejected with a probability of 95% (confidence interval) and the result is considered to have statistical significance.

However, ANOVA is a parametric test and therefore it is necessary to fulfil certain assumptions to use it: normality, homoscedasticity and independence assumptions [50]. In this case, the datasets did not fulfil all the assumptions and a non-parametric test was required. Among these, the Kruskal-Wallis test was chosen [52], as it was considered to be the most convenient for the study developed, given its ability to compare more than two populations.



(a) Average values of the 3 tests (slalom, step input clockwise and counterclockwise) for each trial.



(b) Histograms, distribution and box-whiskers diagrams of the P85-value of the steering operative forces for the three groups in which the steering system has been divided: MS (crossed blue pattern), HPS+EPSc+EPSp (solid green pattern) and EHPS+EPSdp (striped red pattern).

FIGURE 3. P85-value of steering operative forces in driving tests. Based on probability distributions (solid black lines in b), the boundaries are set to F_S^{low} = 18 N and F_S^{high} = 80 N (dashed black lines in a).

III. RESULTS

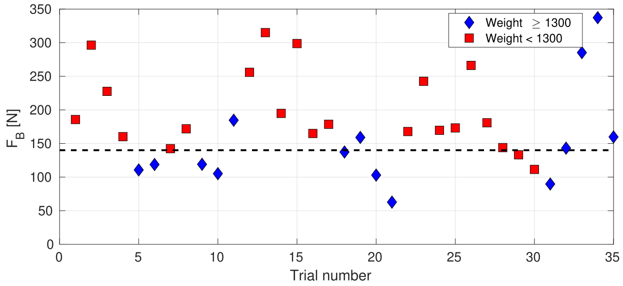
A. STEERING FORCES

1) SLALOM TEST

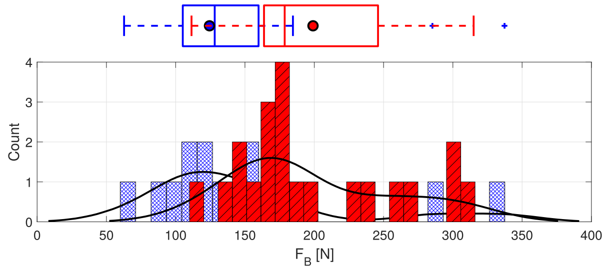
The analysis of the data obtained during the slalom test with the different vehicles and drivers allowed the graphic representation of the forces obtained at the periphery of the steering wheel. The results were clearly differentiated in Figure 3. Thirty-eight testing results were accepted with the criteria described in Section II. For each one of the slalom trials, the force applied to the steering wheel was calculated during the driving movements exercised by the driver as the vehicle circulated between the cones. The values of the peaks for the 5 cones were computed and the P85 was obtained with the absolute minimum and maximum values among the peaks' values. The lateral acceleration was also correlated with the steering torque obtained during the testing trials.

2) STEP INPUT TEST

In the step input testing, data were bounded to the readings obtained between half of the first and last laps in order to get the vehicle data stabilised. The P85 was calculated from the turning force of each trial. In the counterclockwise direction, 38 trials were accepted for analysis.



(a) Maximum braking operative force for each trial.



(b) Histograms, distributions and box-whiskers diagrams of the maximum braking forces for the two groups in which the braking system has been divided, according to vehicle's weight: $w \geq 1300$ kg (crossed blue pattern) and $w<1300$ kg (striped red pattern).

FIGURE 4. Maximum braking forces in driving tests. Based on probability distributions (solid black lines in b), the boundary is set to F_B = 140 N (dashed black line in a).

As a result of the forces measured in the slalom and step input trials, all the values obtained onto the steering wheel were grouped in a single graph. Figure 3 shows the mean values corresponding to P85 steering operative forces obtained during the slalom and step input tests (clockwise or counterclockwise) performed with a specific vehicle and driver, grouped in all cases in terms of operative forces, showing how they were very close one to each other. The forces obtained onto the steering wheel did not differ from one test to another. The results in Figure 3(a) clearly show a trend in the force values applied at the periphery of the steering wheel, helping to identify different levels of forces (two clear thresholds at 18 N and 80 N). These force thresholds were associated with the type of steering assistance system of the tested vehicles. The force levels were in the range of 80 N or more for vehicles of greater hardness in the steering device (mechanical steering systems), around 18 to 80 N for vehicles of medium steering hardness (HPS, EPSc and EPSp), and below 18 N for vehicles of greater steering assistance and very low efforts onto the wheel (EHPS and EPSdp). The statistical significance correlation of these thresholds with the different variables provided valuable, clear and concise information about the influence of each factor in the vehicle operative steering forces.

B. BRAKING FORCES

The maximum force applied onto the brake pedal to stop the vehicle safely in an emergency braking at 50 km/h was calculated with the data acquired in the braking test. There were a total of 35 valid trials for such test, as shown in Figure 4. The average deceleration in the trials was 10.78 m/s^2. A unique brake force threshold can be clearly visualised at $F_B = 140$ N. The statistical significance of this threshold to split both datasets is later demonstrated in Section III-C.

C. STATISTICAL ANALYSIS

For both operative braking and steering forces, a Kruskal-Wallis test was performed for each characteristic variable related to vehicles and drivers, in order to find whether there would be significant differences between populations or not. The most interesting value in Kruskal-Wallis is the P-value, marked in bold in the results tables 3 and 4. When the P-value is smaller than 0.05, it means to be a significant difference in that category with a confidence interval of 95%.

Firstly, the results of the P85 operative forces in steering wheel are shown in table 3, for which the representative forces of the slalom and step input tests were used. As it is shown, power steering type, vehicle antiquity and vehicle length demonstrate to have significant differences between their populations. Bonferroni test was performed to detect which population pairs have a significant difference. In this analysis Bonferroni was only applied to the vehicle antiquity variable. The vehicle antiquity that are significantly different are the ones with less than 10 years of antiquity with respect to the vehicles with more than 20 years of antiquity.

Secondly, regarding braking forces, Kruskal-Wallis results in table 4 show that only weight category had a significant difference with 95% confidence. In this case, the test was not performed with the powered steering type variable, as this is a test where vehicle direction had no influence and therefore this characteristic did not apply.

IV. DISCUSSION

Tables 3 and 4 present the variables that are significantly different from a statistical point of view, and solve the initial non-null hypotheses about the influence of some parameters in relation with the steering wheel and the brake pedal operative forces. After the application of the Kruskal-Wallis and Bonferroni tests, the comparison of the medians and mean values by different populations have been used to identify the statistical significant differences for each category.

A. STEERING OPERATIVE FORCES THRESHOLDS

From the results shown in Figure 3 for operative forces into the steering wheel, it can be observed that vehicles with mechanical steering system require higher forces than other equipped with powered-assisted systems, as HPS, EHPS or EPS. This was really expected, as over the time newer and improved assistance devices have been introduced in the market by manufacturers allowing a substantial reduction of the operative forces applied onto the steering wheel, which comply the technical requirements that fulfil the type approval procedure [24]. So, in this study, different thresholds in the operative forces applied onto the steering wheel have been clearly identified.

TABLE 3. Kruskal-Wallis and Bonferroni tests results for operative steering forces.

Feature	Category	Average rank	Median F_S [N]	Mean F_S [N]	P-value	Bonferroni comparison by pairs	Gap	BSD	Significant difference
Power Steering	HPS + EPS$_c$ + EPS_p	25.50	25.28	25.75	**6e-7**	Bonferroni test is not necessary as this is a two-population category	18.0	7.06	**Yes**
	EHPS + EPS$_{dp}$	7.50	10.36	10.90					
Vehicle Antiquity	$<$ 10 years	13.4	20.27	16.90	**0.0067**	$<$ 10 years - 10-19 years	6.07	8.99	No
	10-19 years	19.5	23.04	20.33		$<$ 10 years - $\geq$ 20 years	20.95	16.16	**Yes**
	$\geq 20 years$	34.3	30.56	30.93		10-19 years - $\geq$ 20 years	14.88	15.62	No
Vehicle Weight	$<$ 1300 kg	19.1	20.28	20.43	0.763	In these tests $P > 0.05$ and, therefore, Kruskal-Wallis does not show significant difference between populations for these categories			
	$\geq 1300kg$	18.0	23.01	19.57					
Vehicle Length	$<$ 4200 mm	22.8	25.48	23.27	**0.015**	Bonferroni test is not necessary as this is a two-population category	8.56	6.88	**Yes**
	$\geq 4200mm$	14.2	15.8	16.68					
Vehicle Segment	B	19.9	21.63	21.31	0.241	In these tests $P > 0.05$ and, therefore, Kruskal-Wallis does not show significant difference between populations for these categories			
	C	17.9	21.75	19.42					
	E	27.0	26.08	26.08					
	Van	6.5	10.42	10.0					
Driver Age	$<$ 30 years	21.9	23.73	21.55	0.087	In these tests $P > 0.05$ and, therefore, Kruskal-Wallis does not show significant difference between populations for these categories			
	$\geq 30years$	17.5	15.8	16.83					
Driver Gender	Men	19.8	23.04	20.99	0.107	In these tests $P > 0.05$ and, therefore, Kruskal-Wallis does not show significant difference between populations for these categories			
	Women	12.2	10.48	14.93					
Driver Experience	$<$ 7 years	20.1	23.46	21.01	0.282	In these tests $P > 0.05$ and, therefore, Kruskal-Wallis does not show significant difference between populations for these categories			
	$\geq 7years$	16.3	19.82	18.53					

TABLE 4. Kruskal-Wallis and Bonferroni tests results for operative braking forces.

Feature	Category	Average rank	Median F_B [N]	Mean F_B [N]	P-value	Bonferroni comparison by pairs	Gap	BSD	Significant difference
Vehicle antiquity	$<$ 10 years	28.5	146.09	165.7	0.185	In these tests $P > 0.05$ and, therefore, Kruskal-Wallis does not show significant difference between populations for these categories.			
	10-19 years	18.8	169.61	182.2					
	$\geq$ 20 years	14.8	241.01	241.0					
Vehicle Weight	$<$ 1300 kg	21.9	178.64	199.1	**0.006**	Bonferroni test is not necessary as this is a two-population category.			**Yes**
	$\geq$ 1300 kg	12.2	128.19	151.1					
Vehicle Length	$<$ 4200 mm	19.3	170.72	181.9	0.508	In these tests $P > 0.05$ and, therefore, Kruskal-Wallis does not show significant difference between populations for these categories.			
	$\geq$ 4200 mm	16.9	159.80	178.2					
Vehicle Segment	B	18.9	170.72	180.2	0.062				
	C	16.9	160.23	171.9					
	E	6.00	114.71	114.7					
	Van	33.0	311.26	311.3					
Driver Age	$<$ 30 years	16.9	167.84	168.0	0.307				
	$\geq$ 30 years	20.8	171.77	209.7					
Driver Gender	Men	18.4	164.90	184.4	0.63				
	Women	16.2	171.38	157.9					
Driver Experience	$<$ 7 years	17.9	170.72	172.7	0.918				
	$\geq$ 7 years	18.2	159.80	192.0					

For mechanical steering systems the results showed steering forces $F_S > 80$ N (steering torque $T_S > 6.8$ Nm). The HPS, EPSc and EPSp systems had a range of forces $F_S = [18-80]$ N (steering torque $T_S = [1.53-6.8]$ Nm), and a mean value of $F_S^{mean} = 25.75$ N. All the vehicles equipped with EHPS and EPSdp powered steering systems showed a force $F_S < 18$ N (steering torque $T_S < 1.53$ Nm), and a mean value of $F_S^{mean} = 10.90$ N. Regarding the antiquity of the vehicle, those models with more than 20 years needed a higher steering operative force than newer ones, as it could be expected (mean F_S value of 30.93 N and 16.90 N, respectively). Vehicles over 20 years of antiquity were designed with purely mechanical steering systems, whose manual operation required more effort than current vehicles.

In relation with vehicle length category, shorter vehicles -with length $l < 4200$ mm, segment A and B-, obtained a higher mean value of steering operative forces than longer ones -$l \geq 4200$ mm, segment C, D and E- (F_S^{mean} of 23.27 N and 16.68 N, respectively), which could be surprising at first. The use of driving assistance systems designed to reduce the efforts applied onto the steering wheel in larger vehicles would justify that, in these cases, the effort required to perform the driving manoeuvres was lower than in the smaller ones. The use of EHPS devices is quite common in this type of vehicles, which would justify the reduction of efforts applied in vehicles of greater length. These vehicles' steering system behaviour were expected initially to be fulfilled, but the results obtained have statistically demonstrated the validity of the method developed.

Regarding the gender category for drivers, men population obtained a higher mean steering force than woman population (F_S^{mean} of 20.99 N and 14.93 N, respectively). This conclusion could be initially expected, although it may be tricky and should be taken with care, as the number of women participating in the study was considerably low, and this part of the results must be improved with more female drivers.

Quantitatively, all these results were consistent with the ones obtained previously [25], [30]. Considering that these research studies were based on vehicles whose data could be considered actually obsolete in the current market, it can be assumed that the force thresholds obtained in the present study contribute substantially to improve the general knowledge about the level of operative forces applied onto the periphery of the steering wheel of up-to-date vehicles.

Considering the two hypotheses planned initially in this study, it has been demonstrated that: firstly, the forces exerted on the steering wheel are independent of the vehicle's weight and segment; and secondly, that the driver's age, gender and experience do not influence the forces exerted on it.

B. BRAKING OPERATIVE FORCES THRESHOLDS

Finally, assuming that all the vehicles tested were equipped with ABS system, in relation with the braking forces F_B applied onto the brake pedal, the results of the mean values for vehicles weighting $w < 1300$ kg showed a higher value than those weighting $w \geq 1300$ kg (F_B^{mean} of 199.1 N and 151.1 N, respectively). This effect was similar to that of the length category in the steering forces, as heavier vehicles usually correspond to vehicles of higher class -segments C, D and E-, and used better servo-assistance braking systems than the lighter ones. That is logical, as heavier vehicles would have more inertia to movement, and would need an improved servo-assisted braking system to stop safely the vehicle in the same distance as lighter ones. In this case, two thresholds could be clearly identified. Those vehicles weighting $w < 1300$ kg would need a brake operative force $F_B > 140$ N, and those vehicles weighting $w \geq 1300$ kg, would need a brake pedal force $F_B \leq 140$ N. These braking forces were consistent with those obtained by [4] and [8] at previous similar studies.

Similarly, the forces exerted on the brake pedal are independent of the vehicle antiquity, the length and segment which they belong to. Likewise, these forces do not depend on the age, gender and experience of the driver.

V. CONCLUSION

The upgrades introduced in the EU Directive (EU) 2015/653 amending Directive 2006/126/EC on the driving license [7] were aimed at facilitating that the maximum force that any driver could make on the vehicle's primary controls could be adjusted to their needs. Specifically, this update resulted in the introduction of new European codes: Code 20.07 – Brake operation with a maximum force of . . . N and Code 40.01 –Steering with a maximum operation force of . . . N. Concretely, these operational forces must be measured in the FtD assessment or, if necessary, with an open-road driving ability test.

The results obtained demonstrated that operative forces on the steering wheel were dependent mainly on the power steering assistance system, vehicle antiquity and vehicle length. Similarly, the forces applied onto the brake pedal were basically dependent of the vehicle weight. The main contribution of this study it is the establishment of a technical criterion on the suitability of using technical aids in the adaptation of vehicles to drivers with disabilities in relation with the codes 20.07 and 40.01 of the European Directive 2015/653 [7]. A new FtD criteria has been proposed and it is described in appendix V.

Basically, the thresholds in the operative forces applied onto the steering wheel are: more than 80 N for MS system, forces between 18 to 80 N for HPS, EPSc and EPSp, and forces below 18 N for EHPS and EPSdp powered steering systems. Vehicles with length shorter than 4200 mm -segment A and B-, needed a higher value of steering operative forces than longer ones -more than 4200 mm, segment C, D and E-. Men population obtained a higher mean steering force capacity than woman population. In relation with the operative braking forces, results showed that vehicles weighting less than 1300 kg would need an operative force onto the brake pedal higher than 140 N, and those vehicles weighting more than 1300 kg, would need a brake pedal force lesser than 140 N.

As future work, the necessary efforts to apply in vehicles belonging to segments A, D, E and Van need to be analysed. Similarly, the study should be expanded with the participation of more women and the elderly, in order to balance the data obtained and consolidate the influence of these variables on the conclusions obtained. Regarding the measurement of the operating forces in the braking system, some characteristics of the vehicle that may affect braking have not been taken into account, such as the tire's condition, the brake type or the use of braking assistance devices, like the emergency braking system (EBS). These parameters could affect the forces exerted on the brake pedal, and therefore their analysis would be recommended as further improvements.

APPENDIX
TECHNICAL CRITERIA TO APPLY CODES 20.07 AND 40.01

For the application of the new technical criteria based on the results obtained in this study, the following premises must be previously met:

1) The measurement of the operative forces onto the steering wheel and the brake pedal must be carried out in driver assessment centres authorised by administration.
2) The measurement of the operative forces must be carried out by qualified technical personnel, assisted by medical specialists or FtD assessors authorised by administration.
3) The measurement of the operative forces onto the steering wheel and brake pedal ought to be carried out with experimental tools capable of measuring forces without movement of the vehicle (static). Examples of tools could be driving simulators or static rigs. These tests must reproduce the usual movements of a steering wheel in both directions and the brake pedal displacement.
4) The objective of the FtD assessment must be to determine the driving ability of the subject assessed, instead of the suitability of the type of vehicle driven.
5) The values obtained in the measurement of the operative forces ought to be contrasted with the reference values, allowing a decision-making criteria based on the thresholds defined in table 5 for the steering system (code 40.01), and table 6 for the brake pedal (code 20.07).
6) All the operative forces obtained in the FtD assessment have to be corroborated later with a driving ability test in an open-road circuit.

TABLE 5. Recommendations about the use of code 40.01 on the steering system during the FtD assessment of driver with disabilities to drive vehicles of category M1 (driving licenses B, BE) according to EU directive 2015/653.

Operative F_S applied by driver	Vehicle steering system needed	Decision making during the fitness to drive assessment of the driver with disabilities/recommendations to the driver
$F \geq 300$ N	Mechanical steering or powered system	Code 40.01 does not apply. The driver can exert enough force even in the case of failure in the vehicle steering system.
$150 < F < 300$ N	Mechanical steering or powered system	Code 40.01 does not apply. The driver can perform enough force above the required value in an intact steering system. No legal consequences for the driver.
$80 < F < 150$ N	Mechanical steering or powered system	Code 40.01 applies For operative forces greater than 80 N and lesser than 150 N, a vehicle with mechanical steering system could be used; If the driving test is passed, it will not be necessary to adapt the steering system.
$18 < F < 80$ N	Powered steering system (HPS, EPSs and EPSp)	Code 40.01 applies For operative forces greater than 18 N and lesser than 80 N, a vehicle with powered steering system (HPS, EPSs and EPSp) may be recommended. The results of the driving test will determine the type of adaptations to be installed in the vehicle steering system.
$5 < F < 18$ N	Powered steering system (EHPS and EPSdp)	Code 40.01 applies For operative forces greater than 5 N and lesser than 18 N, a vehicle with powered steering system (EHPS and EPSdp) may be recommended. The results of the driving test will determine the type of adaptations to be installed in the vehicle steering system. It could be applied codes 33.01 or 33.02 after FtD assessment.
$F \leq 5$ N	Joystick steering system	Code 33.01 0 33.02 is applied according to installed adaptation. A real driving test must be carried out with Joystick-type adaptations to determine the suitability of the driving.

TABLE 6. Recommendations about the use of code 20.07 on the braking system during the FtD assessment of drivers with disabilities to drive vehicles of category M1 (driving licenses B, BE) according to EU directive 2015/653.

Operative F_B applied by driver	Vehicle braking system	Decision making during the fitness to drive assessment of the driver with disabilities / recommendations to the driver
$F > 500$ N		Code 20.07 does not apply. The driver can perform enough force above the required value in an intact braking system. No legal consequences for the driver.
$140 < F < 500$ N		Code 20.07 does not apply. The driver can perform enough force for normal and emergency manoeuvres in an intact braking system.
$90 < F < 140$ N	Powered servo-braking system	Code 20.07 applies. The results of the driving test will determine the need for installing adaptations in the vehicle braking system.
$F < 90$ N	Powered servo-braking system	Code 20.07 applies. For operative forces lesser than 90 N, a vehicle with reinforced powered servo-assisted braking system may be recommended. The results of the driving test will determine the type of adaptations to be installed in the vehicle.

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