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Effects of mobile telephone tasks on driving performance: a driving simulator study

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Abstract

Mobile phone use while driving is increasing among road users. Although the most of countries made illegal the cell phone use while driving, the drivers still use it both for calling and texting. Several studies investigated the distraction factors related to the use of mobile while driving and the effects on road safety. The main findings of these studies generally demonstrated an increasing of reaction time and decreasing of driving performance especially during not critical driving conditions, while the evaluation of the effects of mobile use during critical driving conditions is not so much investigates.
The overall objective of this work is to contribute to the evaluation of the effects of the mobile phone use on driving safety. Specifically the effects of using cellular phone at the same time the driver is faced with making a critical stopping decision are investigated.
The experiments are carried out using an interactive driving simulator. Three different road scenarios (urban road, rural road and motorway) are simulated. Thirty subjects take part to the experiments and drive four times each scenario: one time without calling (control scenario) and the other three times answering the calls by hand-held mobile, hands-free mobile and hands-free voice device. The driver's reaction time, the deceleration rate, the speed and the following distance are evaluated.
The main effects of driving and calling are observed in the urban scenario, where the decreasing of driving performance is much more evident than in the rural and motorway scenario. Not significant differences on driving performances are found across the three telephone modes.

Keywords – mobile phone, hand-held, hands-free, reaction time, driving simulator

1. Introduction

With the strong improvement of communication technologies provided as original equipment in the vehicle and portable equipment brought into the vehicle, the electronic communication devices, such as mobile telephones, are receiving increasing attention regarding their influence on driving performance and road safety.

Although drink driving, speeding and non-wearing of seatbelts remain recurrent key issues in all countries and the experience has shown that efforts on these three fronts bring large benefits, distracted driving, including the use of mobile phones, is now a growing concern in many countries.

1.1. Distracted driving

Distracted driving, which includes a wide range of activities while driving, such as phoning, texting, watching video and regulating the GPS navigator, is recognized as a growing road safety issue by many countries, considering for example the explosion in the sales of mobile phones and in-vehicle technologies. NHTSA [1] estimated that in 2009 the 17% of all road crashes in the United States involved distracted driving, representing nearly 5500 fatalities.

Moreover several studies confirm the attention that must be addressed to this increasing problem demonstrating that from 25 to 50% of road accidents are related directly to distraction (e.g. [2] – [4]). Hendricks et al. [4] observed that crash causes are attributed to either driver behavior or other causes. In 717 of the 723 crashes investigated (99%), a driver behavioral error caused or contributed to the crash. Of the 1284 drivers involved in these crashes, 732 drivers (57%) contributed in some way to the cause of their crashes. The authors found six causal factors associated with driver behaviors that occurred at relatively high frequencies for these drivers and accounted for most of the problem behaviors. They were: driver inattention, vehicle speed, alcohol impairment, perceptual errors, decision errors, and incapacitation (e.g., fell asleep). The driver inattention covered 22.7% of the causality, demonstrating that distraction decreased driving performance, and that consequently the risk of crashes increased. Moreover, according to these results, Larsen and Kines [5] found that the primary accident factors in left-turn accidents are observed to be attention errors.

All these and similar findings support the view that attention is a primary cognitive requirement for safe driving performance.

1.2. The increasing of "phone and driving"

One of the main cause of distracted driving is related to the use of mobile phone during the drive. Mobile phone subscriptions are widely increasing all over the world to values unexpected until few years ago. In particular Eurostat statistics [6] show that the number of mobile phone subscriptions to public mobile telecommunication systems is generally over one per person. Analogously the number of subscriptions in the USA is 91 per 100 inhabitants, 94 in Australia, 64 in Canada; only in very rare cases the number is lower than 50, e.g. in Egypt, Lebanon, Pakistan, Bangladesh (e.g. [7]). Then it is not surprising that more than 85% of cellular telephone owners use their phones at least occasionally while driving, and more than 27% use their phones during half or more of their trips [8]. Similar results are shown in the recent annual report of IRTAD [9].

In the meanwhile the strong improvement of technologies and the consequent wide diffusion of mobile equipment have increased the safety concern especially while driving. Public and legislative sectors as well as the media put in alarm on the safety of using a cellular telephone while driving. Moreover all these concerns have been reflected in the growing number of legislative initiatives in the countries that address the use of wireless communications in vehicles.

1.3. Laws prescribing "phone and driving"

It is from the beginning of nineties that governments consider with more or less awareness the issue of using the cellular phone while driving [9]. Although the most of countries have made the use of the cell phone while driving illegal its use while driving is still common both for calling and texting. Many governments have enacted laws to ban mobile phone use.

Some laws, regulations and recommendations have been promulgated and differ from country to country and sometimes disagree.

The laws prescribing the use of mobile while driving are mostly related to hand held phone, while only in few countries the use of hand free phone is consider illegal (e.g. Australia, Greece, Switzerland [9]).

In general, in the countries where the use of cellular phone is directly associated to some risks, three kinds of measures have been assumed: more than 50 countries have adopted laws prohibiting the use of cellular phones while driving; in few cases some preventive measures have been imposed to cars manufacturers; finally wide media campaigns have been produced to make drivers aware of the associated risks.

2. Literature background

The laws prescribing “phone and driving” are justified by several studies. The first works are developed at the end of sixties (e.g. [10]) with the aim of evaluating driving performance while drivers are involved in a telephone call. All the literature studies start from the following questions: does the use of cellular phone increase the mental work load reducing the attention and the performance of the drivers? does the use of cellular phone reduce the safety of driving? if the safety is reduced, how and how much does the risk increase?

Notwithstanding on the basis of the literature relating to dual-task performance it is reasonable to suppose that concurrent performances of two tasks, as in the case of driving while using a mobile phone, result in poorer performances of either or both, depending on the levels and types of demand of each task and their allocated priorities, it is not certain which is the mechanism of distraction and in which way the safety of driving is reduced.

The first studies that investigated more in depth this mechanism putted in light that the main problem is connected to issues related to manipulation. Briem and Hedman [11] demonstrated that a difficult conversation may affect the driving adversely and any prolonged manipulation of the telephone is liable to produce a performance decrement, particularly under conditions that put heavy demands on the driver's attention and skill. In several studies hands-free mobile, which does not have a manual component and requires only a limited visual demand to operate, and hand-held equipment have been used to distinguish the effects of conversation and manipulation tasks. Brookhuis et al. [12] found that the subjects who operated the hands-free telephone showed better control of the test vehicle than the subjects who operated the hand-held telephone, as measured by the steering wheel movements. Moreover Caird et al. [13] found that hands-free cell phones produced similar performance decrements to hand-held phones. This result should be consider with great attention considering that in general laws and regulations prohibit only the use of hand-held telephone and allow the use of hand-free ones [9], under the implicit hypothesis that manipulation effects are relevant and conversational inattention can be neglected.

It has been demonstrated later that, beyond the simple manipulation, many factors affect the drivers performances. The conversation itself can be a cause of distraction. Strayer et al. [14] assessed the hypothesis that cell phone conversations impair driving performance by withdrawing attention from the visual scene, yielding a form of inattention blindness. The driving simulator study demonstrated that active engagement in the cell phone conversation appeared to be necessary to produce interference with driving. The authors used an incidental recognition memory paradigm to assess what information in the driving scene participants attend while driving. The procedure requires participants to perform a simulated driving task without the foreknowledge that their memory for objects in the driving scene would be subsequently tested. Later the participants are given a surprise recognition memory task in which they are shown objects that are presented while they are driving and are asked to discriminate these objects from foils that are not in the driving scene. The data are consistent with the hypothesis that the cell phone conversation disrupts performance by diverting attention from the external environment associated with the driving task to an engaging internal context associated with the cell phone conversation.

Many studies analyzed the influences of mobile phone on driving performances and particularly on driver's reaction time. Alm and Nilsson [15], using the VTI driving simulator, demonstrated that the use of cellular phone had a negative effect on reaction time, that increased during the call while driving. Furthermore, the drivers did not compensate for their increased reaction time by increasing their headway during the phone task. These evidences were confirmed by Caird et al. [16] that compared under a meta-analysis 84 studies from 1969 to 2004. Sixty-eight articles were research papers measuring driving performance while using a cell phone and 16 articles were epidemiological studies that examined cell phone use and their relationship with road crashes. The studies generally confirmed that the driving performances decreased during the call both using a hand-free and a hand-held equipment. The total mean increase in reaction time analysis was 0.25 s for all manipulations. On the contrary the effects of mobile use on lateral displacement and speed of vehicles were less significant. Later the same authors updated their meta-analysis [13] and found that the effect of conversation on driver performance was to delay recognition and response to important traffic events. Schattler et al. [17] using a driving simulator found that the speed reduced significantly and the reaction time increased while using a hand-held equipment. The authors found that when cell phones were used while driving, subject performance scores were significantly lower. Moreover twice as many crashes were observed when subjects used cell phones while driving as were observed under the control condition.

On the contrary there are few studies that analyze the effects of mobile phone on driving performance under different road environment conditions. Törnros and Bolling [18] studied the effects of cellular phone use, both hand-held and hands-free, while driving in different traffic conditions. The experimented environments were: rural environment with a speed limit of 90 km/h, rural environment with a speed limit of 70 km/h, urban environment of low complexity, urban environment of medium complexity and urban environment of high complexity. Performance on a peripheral detection task (PDT) presented while driving was evaluated. Specifically the authors used the reaction time to detected stimuli and percentage missed PDT signals as a measure of mental workload, according to results of a previous study [19]. Tornos and Bolling found that PDT was impaired by mobile phone conversation in all environments and it was remarkably poor at the complex urban environment, even when the participants were not using the phone. Driving speed was reduced by conversation in all environments for hand-held mode, but only in two environments for hand-free mode (the rural environment with a speed limit of 90 km/h and the complex urban environment). The authors finally assumed that the effects on speed could be interpreted as a compensatory effort for the increased mental workload.

Another important factor that affects literature findings especially on reaction time concerns the critical-not critical situation of the driving when the call is performed. One of the earliest controlled empirical studies of in-vehicle communication distraction was conducted by Brown et al. [10]. The authors evaluated drivers performance at a critical decision point. This is one of the few existing tests that analyzed the influence of concurrent communication task during a stressed driving maneuver. The authors concluded that the hand-held walkie-talkie system, they used for communication, had a critical influence on overall drivers performance. Many studies analyzed the effect of mobile phone during car following situations (e.g. [15, 20]). In the driving simulator study of Strayer et al. [14] the subjects were requested to follow a vehicle that was braking randomly. They measured a number of real-time performance variables to determine how participants reacted to the car braking in front of them. Results revealed that participants began their braking response approximately 1 s after the pace car's brake lights were illuminated and that the participants kept their foot on the brake for about 0.5 s following brake onset. Hanckock et al. [21], basing on a field study, demonstrated the detrimental impact of a coincident in-vehicle phone task on a critical driving maneuver. They recorded a slower response of drivers to the unexpected brake in the dual task condition. Moreover to compensate for this delay, drivers subsequently broke more intensely.

Summarizing the most of literature studies put in evidence that the effects of using a mobile phone while driving were related to the increasing of reaction time [12, 14, 15, 20], the decreasing of driving performance (e.g. [22]), the reduction of speed [15, 17, 18, 23], the increasing of cognitive inattention (e.g. [24, 25]), the reduction of the field of view [26-28].

Several studies had also investigates the effect of mobile use on road safety and risk of accident. Recently Elvik [29] developed a meta-analysis of studies that evaluated the effects on accident risk of using mobile phones while driving. Particularly the author affirmed that the evidence from simulator studies suggested that the net effects on driver behavior of using mobile phones were minor. A tendency was found for reaction time to increase and for speed to decrease with a not significant final effect on the variation of stopping distance. The author explained such surprising result assessing that simulator studies might not necessarily accurately model actual safety margins when driving and it was really important for such analysis where the risk of accident involvement was related to safety margins, like stopping distance. It could explain the different results obtained by the epidemiological studies, analyzed by the author, where it was found that the risk of accident involvement when using a mobile phone increased by a factor of almost three.

In literature there are also some advanced studies (e.g. [21, 30, 31]) carried out on the road or reproducing at the best the real driving situations. In general they compared effects of telephone mode (hands-free versus hand-held) to baseline conditions. According to simulation based studies, the participants' reaction times increased when conversing but no benefit of hands-free units over hand-held units on rural roads/motorways was found.

Moreover other studies based on epidemiological and statistical approaches (e.g. [32, 33]) confirmed the significance of the effects of mobile cellular use on the driving performances.

Finally some studies tried to explain the main causal relationships that are most probably at the basis of the observed effects of reduction of driving performances. In general these relationships are related to the manipulation (e.g. [21, 34]) and to some cognitive mechanisms that differently affect the drivers' attention [35]. Ferlazzo et al. [35] suggested that due to the brain coding the space into multiple representations, devices that made phone conversations taking place in the near, personal space made drivers slower at responding to visual stimuli, compared to devices that made the conversation occurring in a far space.

3. Overall objective

The overall objective of this work is to contribute to the evaluation about if, when and how much the mobile phone tasks affect the safety of driving, specifically when the driver is requested to have an unexpected brake.

Of course the investigation is restricted to some relevant cases in such a way that the results could be considered reasonably valid for a wide set of situations but obviously they can not be generalized to all cases.

The specific objectives of this work, developed with an advanced driving simulator, that are useful to reach the overall objective are:

1. a full scale analysis of the drivers performances (e.g. reaction times, deceleration rates, safety distances) while using hand-held, hands-free and hands-free voice cellular phone;
2. an evaluation of the variability of the drivers performances while using cellular phone in different road scenario (urban road, rural road and motorway).

4. Method and instruments

4.1. Driving simulator

The experiments are developed using the STI driving simulator system at the laboratory of the Inter-university Research Centre of Road Safety, CRISS. The simulator consists in a complete automobile (Alfa Romeo, AlfaSud) positioned in front of three angled projection surfaces (shown in Figure 1) providing the driver with 135° of Useful Field of Vision. The resolution of the visual scene is 1024x768 pixels and the refresh rate is 60 Hz. The data recording system acquires all the parameters at spatial intervals of 3 meters. Two cameras are used to record the driving scene and, simultaneously, the driver. The cameras system makes it possible to localize exactly the moments of ringing of the phone and answering of the driver during the simulation in post processing.

4.2. Scenario and simulation set up

Three different road scenarios are simulated to investigate the effects of mobile use on different road typologies as the authors hypothesized that the influence of mobile communication could vary among different road infrastructure, according to a previous study [18]. Specifically the road scenarios investigated are: scenario A, an urban road with 50 km/h speed suggested to the driver; scenario B, a rural road with 80 km/h suggested speed and scenario C, a motorway where the suggested speed is 110 km/h. The lengths of the scenarios are respectively 3.3 km, 7.5 km and 10.3 km. Figure 2 shows some frames of the simulated scenarios.

Moreover three different ways of using cellular phone are investigated for each scenario:

- hand-held (HH);
- hands-free (HF);
- hands-free voice (HFV).

Fig. 1 - Driving simulator

Fig. 2a - Urban road (Scenario A)

Fig. 2b - Rural road (Scenario B)

Fig. 2c - Motorway (Scenario C)

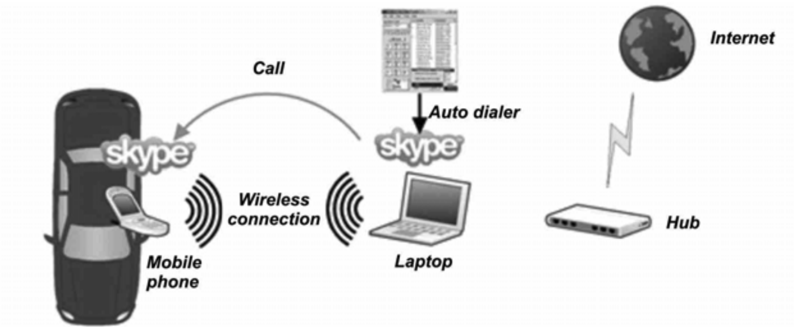

Fig. 3 - Calls equipment

During the simulation of each scenario two calls are made always at the same two roadway sections for all the drivers. The calls are executed following the scheme in Figure 3 using the following equipment: cellular phone Nokia N95, Laptop Compaq 8510w and Skype Autodialer Pro Audacity.

The calls last about 1 minute each and they are pre-recorded. The driver during the call is requested to answer to some simple questions with “no” or “yes”. In this way, any bias from different subjective workload, caused by the complexity of the conversational task, is reasonably negligible or strongly limited. In future programs, it would be expected to test other levels of complexity of the conversional task using a larger sample of drivers to extend the results as much as possible.

Before and during the call several vehicles pass the driver and only one of them, defined as lead vehicle, once passed the driver and moved to the lane of the driver, slowly decelerates to a fixed speed (50 km/h in urban scenario, 80 km/h in rural scenario and 110 km/h in motorway scenario) in order to reproduce always the same initial conditions of the forthcoming sudden brake during the call for all the subjects. Specifically the first unexpected brake of the leading vehicle is achieved along a tangent previously established as well as the second brake occurs at a previously established curve. The description of the whole procedure and more details are described in the next section of the paper.

However after passing the driver, the speed of the lead vehicle is set in order to maintain a constant longitudinal distance with the driver: 32 m in urban scenario, 44 m in rural scenario and 52 m in motorway scenario.

These distances are computed using Equation (1) proposed by the Italian technical regulation for road design [36] according to the reaction distance D_R of the driver, that is the distance traveled by the driver within the reaction time:

$$D_R = 0.78 \cdot V_d - 0.0028 \cdot V_d^2 \quad (1)$$

where V_d is the design speed, here assumed respectively equal to 50 km/h in urban scenario, 80 km/h in rural scenario and 110 km/h in motorway scenario.

4.3. Procedure

Thirty subjects took part to the experiments, selected at the Department of Sciences of Civil Engineering at the University Roma Tre among the students with no experience with simulators. They were equally distributed in gender and had an age between 24 and 34 years to avoid any bias of the outcomes, eventually related to aging. All participants had a valid driving license and had been driving for an average of 8.7 years (range 6–11 years). The experience in driving was reasonably comparable among the subjects. The participants reported having driven an average of 8400 km in the preceding year (range 7000–11000 km).

Each subject drove four times each scenario: one time without calling as control scenario, defined as CC, and the other three times answering the calls by HH, HF and HFV, for an amount of twelve simulation tests.

In order to avoid that drivers could have memory of the scenario and to eliminate any fatigue effects, a standard protocol was used splitting over a week the tests for a single driver that consequently had no more than three tests per day. The order of the simulations was counterbalanced across drivers to avoid order effects.

Furthermore for avoiding any driver's expectation of a sudden brake of the vehicle he/she was following, several vehicles passed the driver during the simulation test: once passed the driver some vehicles remained in the passing lane, some of them moved ahead the driver and decelerated or accelerated, and only one vehicle, the so called lead vehicle, moved to the lane of the driver, slowly decelerated in order to reach the established longitudinal distance for the scenario, maintained such distance modifying the speed in accordance with driver's speed and during the call suddenly broke. Moreover the model and the color of the lead vehicle were randomized across the simulation tests. The brake action of the lead vehicle was set in order to evaluate the driver's reaction to an emergency situation. The lead vehicle broke in all the simulation tests using the same constant deceleration rate of 5 m/s^2 until the complete stop of the vehicle. Also the location of the sudden brakes of the leading vehicle was randomized, but always along the same tangent and the same curve for each scenario.

Tab. 1 - Number of drivers discharged for each scenario (Chauvenet criterion)

Scenario A				***Scenario B***				***Scenario C***			
CC	***HH***	***HF***	***HFV***	***CC***	***HH***	***HF***	***HFV***	***CC***	***HH***	***HF***	***HFV***
2	2	1	2	3	2	2	2	2	0	2	2

The driver's longitudinal speed recorded at the beginning of the braking action of the lead vehicle was used for the validation of drivers simulation output using the Chauvenet criterion [37]. It is a strong statistical test used to determine possible outliers and to decide whether or not a bad data point should be discarded. For this analysis the authors selected the driver's longitudinal speed to limit the dispersion of the distribution of the initial speed of the drivers' braking maneuver within the same scenario. According to the statistical procedure drivers rejected were those whose speed at the beginning of the emergency maneuver showed a probability of obtaining the deviation from the mean less than the inverse of twice the number of measurements. Under such condition, in the worst of the twelve cases, only 3 drivers were outliers and were excluded from final analysis, due to biased outputs revealed. Table 1 summarizes the final results of the Chaveneut criterion.

4.4. Analyses and variables

The authors analyzed the drivers performance during the braking maneuver among the twelve simulation tests. The indicators selected for this analysis include the vehicles speeds and deceleration rates, the drivers reaction time and the longitudinal distance between the driver's vehicle and the lead vehicle. The questions investigated are: (1) does the use of cellular phone affect the driving performance? (2) if yes, are the effects on driving performance different between the control case and HH, HF or HFV case respectively? (3) do the mobile phone effects on driving performance change with the road geometry? To answer these questions the authors have analyzed the following indicators:

- V_i is the initial speed of driver's vehicle when the lead vehicle begins its braking action. This indicator was used for the preliminary data validation previously discussed;
- RT is the driver's reaction time, defined as the time interval between the beginning of the braking action of the lead vehicle (when brake lights are illuminated) and the time when driver begins to press the brake pedal;
- a_{av} is the average deceleration adopted by the driver along the braking maneuver;
- a_{max} is the maximum deceleration adopted by the driver along the braking maneuver;
- t_b is the time the driver keeps his/her foot on the brake pedal;
- d_{min} is the minimum distance recorded along the braking maneuver between the driver's vehicle and the lead vehicle.

5. Results

Tables 2 and 3 summarize the results for the braking maneuvers respectively along the tangent and the curve. The average values of indicators are provided and, in parenthesis, there is the standard deviation of each distribution. Results are discussed in the next chapter.

The Student's *t* Test has been performed between each mobile phone scenario (HH, HF or HFV) and the correspondent control scenario (CC) in order to research the statistically significant differences on indicators among the analyzed scenarios caused by the use of mobile phone factor. The analysis is performed to investigate the effect due to the cell phone use on driving performance.

Tab. 2 - Summary of results for braking along tangent

Braking along tangent							
Scenario		V_i [km/h]	*RT* [s]	a_{av} [m/s²]	a_{max} [m/s²]	t_b [s]	d_{min} [m]
A	CC	49.50 (1.72)	1.34 (0.32)	-5.24 (1.65)	-8.44 (0.48)	2.69 (0.98)	23.45 (2.37)
	HH	49.39 (1.78)	1.57 (0.35)	-5.65 (1.41)	-8.36 (0.51)	2.34 (0.51)	20.36 (3.15)
	HF	50.29 (2.28)	1.59 (0.38)	-5.99 (1.20)	-8.39 (0.38)	2.32 (0.50)	21.51 (2.49)
	HFV	50.94 (2.06)	1.50 (0.32)	-6.07 (1.21)	-8.41 (0.69)	2.29 (0.42)	21.78 (3.64)
B	CC	79.70 (2.83)	1.46 (0.28)	-5.24 (1.36)	-8.55 (0.81)	3.99 (0.71)	23.48 (6.79)
	HH	79.42 (2.77)	1.40 (0.34)	-5.21 (1.73)	-8.53 (0.53)	3.98 (0.90)	25.06 (7.12)
	HF	80.06 (1.85)	1.48 (0.44)	-5.84 (1.37)	-8.57 (0.49)	3.80 (0.75)	25.14 (5.78)
	HFV	80.86 (2.43)	1.46 (0.36)	-5.51 (1.49)	-8.49 (0.72)	3.87 (0.80)	24.39 (6.63)
C	CC	109.62 (2.07)	1.44 (0.56)	-5.03 (1.32)	-8.63 (0.59)	5.73 (1.14)	22.87 (7.18)
	HH	109.62 (1.94)	1.60 (0.35)	-5.11 (1.48)	-8.64 (0.43)	5.81 (1.22)	24.69 (6.97)
	HF	110.16 (1.57)	1.57 (0.38)	-5.12 (1.14)	-8.67 (0.68)	5.67 (0.97)	23.78 (5.86)
	HFV	109.37 (3.05)	1.58 (0.46)	-5.34 (1.41)	-8.63 (0.67)	5.39 (1.10)	25.61 (6.59)

the values in parenthesis are the standard deviations

Tab. 3 - Summary of results for braking along curve

Braking along curve							
Scenario		V_i [km/h]	*RT* [s]	a_{av} [m/s²]	a_{max} [m/s²]	t_b [s]	d_{min} [m]
A	CC	50.62 (1.99)	1.18 (0.24)	-5.02 (1.44)	-8.36 (0.33)	2.69 (0.80)	23.94 (3.14)
	HH	49.97 (2.95)	1.40 (0.32)	-5.73 (1.59)	-8.34 (0.81)	2.39 (0.65)	21.48 (4.12)
	HF	50.47 (1.18)	1.20 (0.30)	-5.68 (1.48)	-8.41 (0.47)	2.44 (0.58)	22.07 (2.97)
	HFV	49.79 (2.10)	1.34 (0.28)	-5.82 (1.42)	-8.36 (0.43)	2.31 (0.52)	20.71 (2.18)
B	CC	78.66 (2.16)	1.83 (0.49)	-5.41 (1.37)	-8.39 (0.61)	3.73 (0.77)	23.97 (5.69)
	HH	76.28 (4.09)	1.95 (0.51)	-5.55 (1.69)	-8.41 (0.37)	3.60 (0.92)	24.83 (6.13)
	HF	77.65 (2.53)	1.87 (0.33)	-5.35 (1.49)	-8.43 (0.46)	3.61 (0.68)	23.12 (6.54)
	HFV	77.58 (2.08)	1.72 (0.39)	-5.49 (1.32)	-8.42 (0.64)	3.64 (0.64)	24.78 (5.96)
C	CC	109.15 (2.11)	1.77 (0.47)	-5.30 (1.23)	-8.58 (0.71)	5.30 (1.39)	23.49 (6.33)
	HH	108.11 (3.79)	1.69 (0.51)	-4.93 (1.16)	-8.53 (0.73)	5.75 (1.51)	25.04 (6.57)
	HF	109.22 (1.73)	1.74 (0.47)	-5.14 (0.98)	-8.61 (0.81)	5.52 (0.95)	22.69 (5.88)
	HFV	109.04 (1.96)	1.63 (0.49)	-5.03 (1.38)	-8.59 (0.64)	5.80 (1.10)	23.78 (6.49)

the values in parenthesis are the standard deviations

Table 4 provides the results of the statistical analysis performed on each driver's indicator, comparing the distributions of the same driving performance recorded along the control scenario and along each mobile scenario.

Table 5 gives the results of the statistical analysis performed on each driver's indicator, comparing the distributions of the same driving performance across the different mobile types investigated.

In both Tables 4 and 5 the cases that demonstrate a significant variation among scenarios (when the level of significance p is lower than 0.05), are written in bold, while when the p value falls in the 0.051 - 0.10 range, it is written in bold and italic.

6. Discussion

6.1. Reaction time

In the experiments the drivers have to react to the sudden braking of the lead vehicle to avoid the collision. The reaction times of drivers in the control scenario, without calling, and in the three scenarios, using cellular phone by HH, HF and HFV have been computed and compared. In this experiments the reaction time has been evaluated from the beginning of the lead vehicle braking and the instant when driver begins the pressure on brake pedal.

Tab. 4 - Summary of results of the statistical analysis

Scenario			Tangent					Curve				
			RT	a_{av}	a_{max}	t_b	d_{min}	*RT*	a_{av}	a_{max}	t_b	d_{min}
A	HH-CC	*t*	**2.566**	.999	.604	***1.676***	**4.148**	**2.910**	***1.751***	.121	1.540	**2.513**
		p	**.013**	.322	.548	***.099***	**<.01**	**<.01**	***.086***	.904	.129	**.015**
	HF-CC	*t*	**2.682**	***1.968***	.437	***1.805***	**3.011**	.277	***1.706***	.463	1.354	**2.311**
		p	**.010**	***.054***	.664	***.076***	**<.01**	.783	***.094***	.645	.181	**.025**
	HFV-CC	*t*	***1.871***	**2.146**	.189	***1.985***	**2.034**	**2.296**	**2.093**	.001	**2.107**	**4.471**
		p	***.067***	**.036**	.851	***.052***	**.047**	**.026**	**.041**	.999	**.040**	**<.01**
B	HH-CC	*t*	.713	.071	.109	.046	.842	.889	.337	.148	.563	.539
		p	.479	.943	.914	.964	.404	.378	.738	.883	.575	.592
	HF-CC	*t*	.200	1.629	.111	.964	.978	.356	.155	.275	.613	.513
		p	.842	.109	.912	.339	.333	.723	.877	.784	.542	.610
	HFV-CC	*t*	.001	.701	.291	.588	.503	.923	.221	.179	.472	.515
		p	.999	.486	.772	.559	.617	.360	.826	.859	.639	.609
C	HH-CC	*t*	1.314	.217	.074	.257	.979	.614	1.179	.264	1.178	.914
		p	.194	.829	.941	.798	.332	.542	.243	.793	.244	.365
	HF-CC	*t*	1.016	.273	.235	.212	.520	.237	.538	.147	.691	.490
		p	.314	.786	.815	.833	.605	.814	.593	.883	.492	.626
	HFV-CC	*t*	1.022	.849	.001	1.136	1.488	1.091	.773	.055	1.493	.169
		p	.311	.399	.999	.261	.143	.280	.443	.956	.141	.866

Tab. 5 - Summary of results of the statistical analysis across phone usage types

Scenario			Tangent					Curve				
			RT	a_{av}	a_{max}	t_b	d_{min}	*RT*	a_{av}	a_{max}	t_b	d_{min}
A	HH-HF	*t*	.206	.982	.252	.149	1.532	**2.435**	.123	.401	.307	.622
		p	.837	.331	.802	.882	.131	**.018**	.903	.690	.760	.537
	HH-HFV	*t*	.781	1.196	.308	.401	1.561	.747	.223	.115	.509	.874
		p	.438	.237	.759	.690	.124	.458	.824	.909	.613	.386
	HF-HFV	*t*	.965	.251	.136	.245	.328	***1.820***	.364	.419	.890	***1.965***
		p	.338	.803	.892	.807	.744	***.074***	.717	.677	.377	***.054***
B	HH-HF	*t*	.761	1.512	.293	.813	.046	.697	.470	.179	.046	1.009
		p	.450	.137	.770	.420	.963	.489	.640	.858	.963	.317
	HH-HFV	*t*	.641	.695	.238	.483	.364	***1.896***	.148	.072	.189	.031
		p	.524	.490	.814	.631	.717	***.063***	.883	.943	.851	.975
	HF-HFV	*t*	.186	.863	.486	.338	.451	1.554	.372	.067	.170	.993
		p	.853	.392	.629	.737	.654	.126	.711	.947	.866	.325
C	HH-HF	*t*	.313	.029	.202	.481	.536	.387	.742	.396	.689	1.432
		p	.755	.977	.840	.632	.594	.700	.461	.694	.494	.158
	HH-HFV	*t*	.187	.605	.068	1.373	.516	.456	.299	.332	.143	.734
		p	.852	.548	.946	.175	.608	.650	.766	.741	.887	.466
	HF-HFV	*t*	.089	.642	.222	1.010	1.098	.857	.344	.102	1.019	.659
		p	.930	.524	.825	.317	.277	.395	.732	.919	.313	.513

It is found that the reaction time generally increases if the driver is involved in a call respect to the control scenario. This is true always for urban road, both along the tangent and curve and for all the mobile equipments investigated; on the contrary for the rural road the reaction times do not change significantly and in some cases they even decrease (HH along tangent and HFV along curve); in scenario C the reaction time recorded in HH, HF and HFV is quite similar to the reaction time of the control scenario for tangent geometry while it increases with the mobile use for the braking along the curve.

Specifically considering all the cases and averaging also in the cases of reduction of reaction time it is observed that the reaction time increases significantly only in the scenario A for all the types of mobile phone with a level of significance lower than 0.05 (excluded HFV along tangent where p=0.067 and HF along curve where p value is quite high). The results obtained are similar for tangent and curve and for hand-held, hands-free and hands-free voice scenarios as demonstrated in Table 5 where the only significant difference is recorded between HH and HF along the curve of the urban scenario.

Moreover the differences among the reaction time in the control scenario and the other scenarios have been calculated (see Equation 2), to evaluate if it changes significantly while using cellular phone. These differences are estimated separately along the tangent and the curve.

$$\Delta RT = RT_{HH/HF/HFV} - RT_{CC} \tag{2}$$

where $RT_{HH/HF/HFV}$ is the reaction time evaluated along one of the three scenarios with mobile phone (respectively hand-held, hands-free and hands-free voice) and RT_{CC} is the reaction time computed along the control scenario.

Table 6 provides the data related to the drivers for which the reaction time recorded during the simulation tests with the mobile phone is higher than in the control scenario. In these cases where reaction time increases, the average value of reaction time is from 0.19 to 0.57 seconds higher than in the control scenario.

More specifically when the braking maneuver occurs along the tangent, in scenario A the percentages of drivers who show delayed response with phone usage are 75% (HH), 62%(HF) and 57% (HFV), in the scenario B are 32% (HH), 57% (HF) and 46% (HFV) and finally in the scenario C 60% (HH), 64% (HF) and 57% (HFV). Similar results are found for braking along the curve. It appears that the reaction times increases for the most of drivers, especially if the cellular phone is used as hand-held.

The results about reaction time of the present paper confirm the most of the previous findings of literature studies (e.g. [15, 17, 18]) that demonstrated the increase of reaction time when driving during a call. For example Caird et al. [13, 16], analyzing the outcomes of many studies, demonstrated that the mean increase in reaction time is a little bit greater than 0.2 seconds, the standard deviation is from 0.17 to 0.31 seconds. This is basically confirmed by this study with significant results limited to the urban road scenario. Moreover the results confirm the findings of a field study of Hanckock et al. [21] that demonstrated that drivers provided slower reaction to the unexpected brake. Specifically the authors found that drivers exhibited a significantly slower brake reaction time in the presence of the distracter (the call) versus its absence (0.71 s versus 0.52 s).

Tab. 6 - Reaction Times (for the cases where ΔRT>0)

Scenario A Call along Tangent				**Scenario A Call along Curve**			
Mobile type	*HH*	*HF*	*HFV*	*Mobile type*	*HH*	*HF*	*HFV*
# drivers with ΔRT>0	21	18	16	# drivers with ΔRT>0	20	11	18
% drivers with ΔRT>0	75%	62%	57%	% drivers with ΔRT>0	71%	38%	64%
Average ΔRT [s]	0.43	0.57	0.45	Average ΔRT [s]	0.42	0.19	0.35
Standard deviation [s]	0.34	0.30	0.30	Standard deviation [s]	0.22	0.21	0.30
Scenario B Call along Tangent				**Scenario B Call along Curve**			
Mobile type	*HH*	*HF*	*HFV*	*Mobile type*	*HH*	*HF*	*HFV*
# drivers with ΔRT>0	9	16	13	# drivers with ΔRT>0	17	14	12
% drivers with ΔRT>0	32%	57%	46%	% drivers with ΔRT>0	61%	50%	43%
Average ΔRT [s]	0.33	0.31	0.27	Average ΔRT [s]	0.47	0.54	0.51
Standard deviation [s]	0.26	0.16	0.20	Standard deviation [s]	0.33	0.34	0.32
Scenario C Call along Tangent				**Scenario C Call along Curve**			
Mobile type	*HH*	*HF*	*HFV*	*Mobile type*	*HH*	*HF*	*HFV*
# drivers with ΔRT>0	18	18	16	# drivers with ΔRT>0	13	15	11
% drivers with ΔRT>0	60%	64%	57%	% drivers with ΔRT>0	43%	54%	39%
Average ΔRT [s]	0.52	0.45	0.47	Average ΔRT [s]	0.44	0.23	0.36
Standard deviation [s]	0.27	0.26	0.45	Standard deviation [s]	0.35	0.19	0.35

6.2. Deceleration

Drivers' decelerations during the braking action are analyzed in terms of the average value a_{av}, the maximum deceleration rate a_{max} and the time the driver keeps his foot on the brake pedal t_b. From Tables 2 and 3 it is possible to note that the maximum deceleration recorded during the braking maneuver is almost the same in all the scenarios analyzed. On the contrary the average deceleration is different from control scenario to mobile phone scenarios: it occurs significantly for urban scenario where the use of all the mobile equipments lead to an increase of the a_{av} both along the tangent and along the curve. Comparing the a_{av} of each scenario with the average deceleration of the lead vehicle (5 m/s^2) it is evident that it is absolutely higher. It can be explained by the drivers' need for adopting an higher deceleration caused by the delay of their reaction times to the braking action. It is evident also analyzing the maximum deceleration rate. This results is in accordance with Hanckock et al. [21] where the authors showed that to compensate the delay in response time, the drivers subsequently broke more intensely.

The same results obtained for the average decelerations are found for the time the driver keeps his foot on the brake pedal during the braking maneuver: also in this case the significant differences are recorded only on scenario A where t_b is higher in the control scenario rather than in all the mobile scenarios. It occurs for both tangent and curve geometry.

Finally it can be stressed that the only effects of mobile use in terms of deceleration are recorded in urban road, braking along curve and tangent, and with almost the same significant results for all the mobile equipment investigated as shown in Table 5.

6.3. Minimum longitudinal distance

The distance between driver and the lead vehicle is recorded continuously along the simulation. The average minimum longitudinal distance within each mobile phone scenario is evaluated and compared with the average minimum longitudinal distance within the same road segment recorded on the control scenario. Table 2 summarizes the results and provides the minimum longitudinal distance d_{min} of each scenario averaged among the sample of drivers.

The standard deviation of each distribution of minimum distance of drivers is also provided (in the parenthesis, next to the average values). More in depth in the HH, HF and HFV scenarios the average minimum longitudinal distance is lower (from 1.67 meter to 3.23 meters) than the distances recorded in the control scenario. Similar results are found for all the cases of urban road with significant differences, above all for the braking along the curve. Conversely in rural scenarios d_{min} increases for the most of the cases but with no significant differences. Moreover the cases with a decreasing of d_{min} from control scenario to mobile scenario are higher than 50% for each scenario only in the case of urban road.

Such results confirm one more time that the effect of mobile use on driver's performances seem to be significant only in urban scenario. Moreover no significant differences are recorded across the mobile types.

Finally an interesting result is that, although the initial distance between the lead vehicle and the driver's vehicle is different among scenarios (32 m in urban scenario, 44 m in rural scenario and 52 m in motorway scenario), the minimum longitudinal distance reached in all the simulations varies only from 20.36 to 25.61 as to indicate that driver has an own threshold of safety distance to respect also during an emergency maneuver. Moreover the differences among minimum longitudinal distance in the control scenario and the other scenarios have been calculated (see Equation 3), to evaluate if it changes significantly while using cellular phone. These differences are estimated separately along the tangent and the curve.

Tab. 7 - Minimum longitudinal distances (for the cases where Δd_{min}<0)

Scenario A Call along Tangent				Scenario A Call along Curve			
Mobile type	*HH*	*HF*	*HFV*	*Mobile type*	*HH*	*HF*	*HFV*
# drivers with Δd_{min}<0	17	19	15	# drivers with Δd_{min}<0	19	16	16
% drivers with Δd_{min} <0	61%	66%	54%	% drivers with Δd_{min} <0	68%	55%	57%
Average Δd_{min} [m]	-4.91	-4.05	-4.77	Average Δd_{min} [m]	-4.37	-4.01	-4.85
Standard deviation [m]	1.98	2.34	2.13	Standard deviation [m]	1.75	1.97	1.69
Scenario B Call along Tangent				**Scenario B Call along Curve**			
Mobile type	*HH*	*HF*	*HFV*	*Mobile type*	*HH*	*HF*	*HFV*
# drivers with Δd_{min}<0	12	15	13	# drivers with Δd_{min}<0	16	17	14
% drivers with Δd_{min} <0	43%	54%	46%	% drivers with Δd_{min} <0	57%	61%	50%
Average Δd_{min} [m]	-5.73	-4.42	-4.58	Average Δd_{min} [m]	-5.21	-4.86	-5.13
Standard deviation [m]	3.71	3.56	4.13	Standard deviation [m]	3.53	4.69	5.04
Scenario C Call along Tangent				**Scenario C Call along Curve**			
Mobile type	*HH*	*HF*	*HFV*	*Mobile type*	*HH*	*HF*	*HFV*
# drivers with Δd_{min}<0	10	13	9	# drivers with Δd_{min}<0	12	16	14
% drivers with Δd_{min} <0	33%	46%	32%	% drivers with Δd_{min} <0	40%	57%	50%
Average Δd_{min} [m]	-5.78	-6.13	-4.96	Average Δd_{min} [m]	-5.71	-4.22	-3.97
Standard deviation [m]	4.37	4.49	4.16	Standard deviation [m]	4.12	4.86	4.13

$$\Delta d_{\min} = d_{\min HH/HF/HFV} - d_{\min CC} \tag{3}$$

where $d_{minHH/HF/HFV}$ is the minimum longitudinal distance evaluated along one of the three scenarios with mobile phone (respectively hand-held, hands-free and hands-free voice) and d_{minCC} is the minimum longitudinal distance computed along the control scenario during the braking maneuver.

Table 7 provides the data related to the drivers for which the minimum longitudinal distance recorded during the simulation tests with the mobile phone is lower than in the control scenario. In these cases, where minimum longitudinal distance decreases, the average value of minimum longitudinal distance is from 3.97 to 6.13 meters shorter than in the control scenario. More specifically when the braking maneuver occurs along the tangent, in scenario A the percentages of drivers that showed a lower minimum longitudinal distance with phone usage are 61% (HH), 66% (HF) and 54% (HFV), in the scenario B are 43% (HH), 54% (HF) and 46% (HFV) and finally in the scenario C 33% (HH), 46% (HF) and 32% (HFV). Similar results are found for braking along the curve. It is evident that the minimum longitudinal distance decreases in the most of the cases, especially if the cellular phone is used as hands-free.

7. Conclusions

This paper approaches the topic of phone and driving by analyzing drivers' performance in a driving simulator. This paper enhances our overall knowledge by extending traditional approaches to the analyses of driver performance and the evaluation of mobile phone effects.

Specifically the effects of different types of phone usage are investigated comparing results with a control case. Moreover different types of road are simulated. The paper shows the effects of using cellular phone while driving in a motorway, rural and urban scenario, as the driver is requested to react to a sudden brake and demonstrates how the same effects change if a hand-held phone, hands-free phone or hands-free voice systems are used. Of course the investigation is restricted to some relevant cases in such a way that the results could be considered reasonably valid for a wide set of situations but obviously they can not be generalized to all cases. In particular, in accordance with the most of literature studies on this topic, the main effects are recorded on reaction time that generally increases using a mobile equipment.

The analysis also demonstrates that the increasing of the reaction time and the decreasing of the other investigated driving performance are significant only in the urban scenario. Conversely there are no significant effects on driving performance for motorway and rural road.

Moreover the authors find that there are no significant differences across the type of mobile equipment (hand-held, hands-free or hands-free voice) confirming the findings of many previous studies.

Finally almost the same effects on driving performance are recorded along both the tangent and curve. Although the results of this study are promising and confirm many previous literature findings, additional simulator studies are planned. Further validation studies that vary the distraction condition and consequently the mental workload of drivers should be performed to confirm these findings and strengthen and generalize the results. Specifically, the analyses should be extended to larger samples of drivers and different road categories and geometries and should take into account the effects of different and more complex conversational tasks.

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