Analysis of an advanced driver-assistance system to improve safety of cyclists overtaking by driver characteristics

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Abstract

As part of the European Horizon 2020 project i-DREAMS, a medium-fidelity driving simulator study was conducted to evaluate safety effects of a new advanced driver-assistance system (ADAS) on cyclists overtaking by cars. The proposed ADAS was designed with a multimodal human-machine interface, auditory as well as visual information, using a multistage warning system, alerting drivers well in advance about the potential danger so that an imminent collision with the cyclist may be avoided due to attentive drivers. The warning strategy is based on a combination of lateral clearance and time-to-danger parameters.

Forty-eight drivers drove the two-lane rural highway experimental route twice, without and with the ADAS, in three different car-to-cyclist overtaking scenarios. Statistical tests were performed to evaluate the effects of drivers' gender and age on the effectiveness of the ADAS system. Overall, the study results show that the proposed in-vehicle driving assistance system had a significant effect in increasing the lateral clearance and in reducing the aerodynamics forces that can destabilize the cyclist overtaken by car. The ADAS system was more effective for female and older drivers. Finally, the implementation in real word of the proposed driving aid system will have positive impacts on cyclist safety and comfort, making the car-to-cyclist overtaking less dangerous.

Keywords: ADAS, overtaking, multimodal warning, multilevel warning.

1. Introduction

Cyclists are particularly vulnerable because they must frequently share the same infrastructures as motorized vehicles, and yet bicycles offer their users no physical protection in the event of a crash. Part of the kinetic energy released during a car accident will be 'absorbed' by the cyclist's body, and when the amount of external force exceeds the physical threshold tolerated by the human body, severe or fatal injury will occur (Broughton, 2005). The highest number of collisions causing serious injuries to cyclists is on rural roads, due to the significant difference in the speeds of the cars and bicycles (Behnood and Mannering, 2017; Kovaceva et al., 2018; Farah et al., 2019). Notably, among these collisions are those that occur when cars overtake cyclists. When cars and cyclists share the same lane, cars typically need to overtake cyclists, which creates dangerous interactions.

The risk for cyclists during the moment of overtaking is not only determined by the possibility of being involved in a direct impact with the motorized vehicle, such as a rear-end collision or sideswipe, but also, even when there is no collision, overtaking can destabilize cyclists due to the turbulence created by the passing vehicle (Llorca et al., 2017; Gromke and Ruck, 2021; Saxton and Thorp, 2021). These turbulence-related problems are correlated with high vehicle speeds and insufficient passing distances (Shackel and Parkin, 2014).

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A key factor in reducing the risk of negative interactions between motorized vehicles and cyclists is finding the correct lateral clearance (LC) during the passing phase (Rubie et al., 2020).

In this study, and as part of the European Horizon 2020 project i-DREAMS, a new advanced driver assistance system (ADAS) which supports drivers as they overtake cyclists was designed to avoid or, at least, mitigate crashes. In the design of its human-machine interface (HMI), the information was presented via multiples modalities to reduce transmission errors and enhance safety (Schwarz and Fastenmeier, 2017). Moreover, we proposed a multistage warning system in which the early warning stage, more frequent and potentially more annoying for drivers, will be less intrusive, whereas later warning stages will have stronger salience to certainly elicit a driver reaction in an emergency (Winkler et al., 2018). Finally, the warning strategy is based on a combination of lateral clearance (LC) and time-to-danger (TTD) to guarantee both lateral and longitudinal control of a vehicle during overtaking.

The aims of this study are to evaluate the effectiveness and safety benefits of the designed in-vehicle driving aid system, also in effectively reducing the aerodynamic forces experienced by the cyclist when being overtaken, and to investigate the effect of socio demographic background factors (age and gender) on the effectiveness of the system.

2. Experiment

2.1. Design of car-to-cyclist overtaking warning system

An ADAS system was designed to support drivers during cyclist passing manouver helping them to maintain safe lateral distance from cyclist. The driving aid system consists of a multimodal HMI using a multistage warning system that timely makes aware drivers of the presence of the cyclists ahead and alerts them of the potential danger or an imminent collision during overtake manouver. The drivers were alerted by a combination of both imagery and audio signals, which respectively change in colour and intensity in the three phases (Figure 1). Three warning phases were defined: (1) normal driving, (2) danger phase, and (3) avoidable accident phase.

In the normal driving phase, a visual alert icon informs the driver about the presence of the cyclist at safe lateral distance (green double-arrow) from the car. During the danger phase, the warning system presents an orange double-arrow along with a beep sound to alert inattentive drivers. In the avoidable accident phase, the double-arrow becomes red, and the auditory advice is a double beep sound.

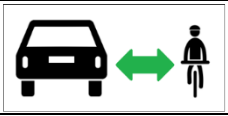
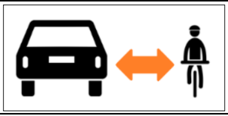
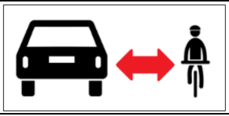
Signal \ Phase	Normal driving	Danger phase	Avoidable accident phase
Visual			
Audio	No acoustic signal	Single Beep	Double high-pitched beep

Figure 1: ADAS warning phases

Considering that drivers are required to laterally and longitudinally control their vehicle to perform a safe cyclist passing (Dozza et al., 2016), a combination of LC and TTD was chosen as warning system. Optimum timing to activate the three warning phases was designed after a comprehensive review of the literature and a pilot study. The LC was used to lateral control of the vehicle and it is the minimum lateral distance between the vehicle and the cyclist during overtaking. The LC threshold values have been defined: (1) LC ≥1.5 m; (2) LC ≥ 1.0 m and LC < 1.5 m; and (3) LC < 1.0 m (Dozza et al., 2014; Shackel and Parkin, 2014). The TTD was used to longitudinal control of the vehicle. It is an extension of Time-to-collision (TTC), and it has been defined as the time taken for the vehicle to laterally align its front bumper with the rear wheel of the cyclist.

The TTD threshold values have been defined: (1) TTD≥3.0 s and TTD≤6.0 s; (2) TTD≥ 2.0 s and TTD < 3.0 s; and (3) TTD < 2.0 s. The combination of LC and TTD during cyclists overtaking maneuver to activate the warning phases was reported (Table 1).

Table 1. Warning Criterion as combination of LC and TTD

		Time to Danger		
		4.5 s > TTD ≥ 3 s	**3 s > TTD ≥ 2 s**	**TTD < 2 s**
Lateral Clearance	**LC ≥ 1.5 m**	Normal diving	Normal diving	Normal diving
	1.5 m > LC ≥ 1.0 m	Normal diving	Danger	Danger
	LC < 1.0 m	Normal diving	Danger	Avoidable Accident

2.2. Study design

The study was conducted on a fixed-base, medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated) at the Transportation Research Institute (IMOB) of Hasselt University in Belgium.

The simulated road consisted of a two-lane rural highway, with lane width of 3.00 m and no shoulders. No separated cycle lane was designed so both motor vehicles and cyclists had to share the experimental rural road lanes. No mark (symbol, sign or marking) was installed to warn of the presence of cyclists on the road.

Three events were tested during the experiment: Event 1 (E1) - overtaking a cyclist riding normally with a constant lateral position (close to the edge line); Event 2 (E2) - overtaking cyclist that manoeuvres from the edge of the lane to the center of the lane; and Event 3 (E3) - overtaking two cyclists riding in parallel position (the first close to the edge line and the second on the center of the lane).

All the three events were designed to take place in tangent, and each of them was repeated three times along the experimental road. The cyclists had a constant speed of 18 Km/h. To prevent confounding errors, the sequence in which subjects encountered each event through the route was balanced and was determined randomly.

Fourty-eight participants (Table 2) was engaged in nine car-to-cycle overtaking events resulting from the three-time repetition of each basic event (E1, E2 and E3). No simulator sickness was observed.

Table 2: Driver characteristics

Driver characteristics	Categories	N	%
Gender	Female	27	56.25%
	Male	21	43.75%
Age	18-25	11	22.92%
	26-35	22	45.83%
	>36	15	31.25%

3. Analysis methods

To study the driver behavior during cyclist overtaking, LC and the maximum aerodynamic force were extracted and analyzed at the point of load of maximum pressure. The maximum pressure force acting on the cyclist was calculated using the equation of Gromke and Ruck (2021):

$$\Delta F_{f0} = c_1 V_{veh}^2 \quad (1)$$

where c_1 is a prefactor determined for each overtaking distance and cyclist type. In our study c_1 was calculated for touring bikes according to the following equation:

$$c_1 = 0.016 \times A_{lc} \times LC^{-1.33} \quad (2)$$

The projected lateral area A_{lc} was set equal to 1 since the vehicle and the bicycle are always the same in the different drives. Given the normality and homoscedasticity of the data, t-student test was carried out to evaluate the effect of drivers' gender and age on the effectiveness of the ADAS system.

4. Results and conclusions

When the ADAS system was inactive, female drivers exhibited shorter LC from the cyclist than male drivers (1,520 m vs. 1,705 m), this difference was statistically significant with p-value equal to 0.001, showing a women's greater risk perception of possible head on crashes (Tables 3 and 4). In the presence of active ADAS system, there was a statistically significant increase in LC for both female drivers (23%, p-value <0.001) and male drivers (10%, p-value = 0.001) but no significant gender difference were found in LC.

Table 3 Mean and standard deviation of LC: ADAS vs Drivers Gender

	Not active (A0)		Active (A1)		$\frac{(LC_{A1}-LC_{A0})}{LC_{A0}}$[%]
Gender	Mean LC [m]	St. Dev. [m]	Mean LC [m]	St. Dev. [m]	
F	1.520	0.509	1.870	0.537	23.005
M	1.705	0.570	1.880	0.526	10.203
Total	1.625	0.551	1.875	0.530	15.445

Table 4 T- tests of LC: ADAS vs Drivers Gender

		Not active (A0)		Active (A1)	
Not active (A0)	Gender	F	M	F	M
	F	1	**0.001**	**<0.001**	**<0.001**
	M		1	**0.002**	**0.001**
Active (A1)	F			1	0.856
	M				1

In the presence of ADAS system active, aerodynamic forces (ΔF_{f0}) showed a statistically significant reduction, equal to -1.335 N (p-value <0.001) for female drivers and -1.146 N for male drivers (p-value <0.001) (Tables 5 and 6). However, both in A0 and in A1, significant gender differences were not found in the aerodynamics forces.

Table 5 Mean and standard deviation of ΔF_{f0}: ADAS vs Drivers Gender

Gender	Not active (A0)		Active (A1)		$\frac{\Delta F_{f0\ A1} - \Delta F_{f0\ A0}}{\Delta F_{f0\ A0}}$ [%]
	Mean ΔF_{f0} [N]	St. DevΔF_{f0} [N]	Mean ΔF_{f0} [N]	St. Dev. ΔF_{f0} [N]	
F	4.141	3.611	2.807	2.224	-32.232
M	4.330	5.500	3.184	2.509	-26.470
Total	4.248	4.762	3.019	2.393	-28.928

Table 6 T- tests of ΔF_{f0}: ADAS vs Drivers Gender

		Not active (A0)		Active (A1)	
	Gender	F	M	F	M
Not active (A0)	F	1	0.684	**<0.001**	**0.001**
	M		1	**<0.001**	**0.003**
Active (A1)	F			1	0.104
	M				1

In the baseline condition (A0), there was a statistically significant reduction of LC with the age (p-value <0.005), starting from 1.824 m for the younger drivers' group ([18;25]), passing to 1.629 m for drivers aged between 26 and 35 years and finishing at 1.493 m for the older drivers' group (>35). With the ADAS system active (A1), these differences among the age groups were eliminated, leveling LC towards higher values (about 1.870 m).

The ADAS system produced a statistically significant increase of LC for drivers older than 26, equal to 0.249 m (p-value <0.001) for drivers aged between 26 and 35 years and 0.379 m (p-value <0.001) for drivers older than 35 years (Tables 7 and 8).

Table 7 Mean and standard deviation of LC: ADAS vs Drivers Age

Age groups	Not active (A0)		Active (A1)		$\frac{(LC_{A1} - LC_{A0})}{LC_{A0}}$ [%]
	Mean LC [m]	St. Dev. [m]	Mean LC [m]	St. Dev. [m]	
[18; 25]	1.824	0.486	1.874	0.490	2.745
[26; 35]	1.629	0.570	1.879	0.537	15.305
>35	1.493	0.530	1.872	0.549	25.351
Total	1.624	0.551	1.875	0.530	15.445

Table 8 T- tests of LC: ADAS vs Drivers Age

		No active (A0)			Active (A1)		
		[18; 25]	[26; 35]	>35	[18; 25]	[26; 35]	>35
No active (A0)	[18; 25]	1	**0.005**	**< 0.001**	0.492	0.414	0.501
	[26; 35]		1	**0.025**	**< 0.001**	**< 0.001**	**< 0.001**
	>35			1	**< 0.001**	**< 0.001**	**< 0.001**
Active (A1)	[18; 25]				1	0.949	0.972
	[26; 35]					1	0.910
	>35						1

Except for drivers aged between 18 and 25 years, the ADAS system produced a statistically significant reduction of ΔF_{f0}. The observed reduction is equal to 2.518 N (45%, p-value<0.001) for drivers older than 35 years, and to 0.856 N (24%, p-value <0.001) for drivers aged between 26 and 35 years (Tables 9 and 10). Both the reductions of the aerodynamic forces were due to the speed reduction and, especially, to the increase of the LC.

Table 9 Mean and standard deviation of ΔF_{f0}: ADAS vs Drivers Age

Age groups	Not active (A0)		Active (A1)		$\frac{(\Delta F_{f0\ A1} - \Delta F_{f0\ A0})}{\Delta F_{f0\ A0}}$ [%]
	Mean ΔF_{f0} [N]	St. DevΔF_{f0} [N]	Mean ΔF_{f0} [N]	St. Dev. ΔF_{f0} [N]	
[18; 25]	3.689	3.396	3.702	3.424	0.345
[26; 35]	3.563	2.828	2.707	1.626	-24.010
>35	5.538	6.902	3.020	2.429	-45.465
Total	4.248	4.762	3.019	2.393	-28.928

Table 10 T-student of Speed of ΔF_{f0}: ADAS vs Driver Age

		No active (A0)			Active (A1)		
		[18; 25]	[26; 35]	>35	[18; 25]	[26; 35]	>35
No active (A0)	[18; 25]	1	0.742	**0.019**	0.980	**0.001**	*0.081*
	[26; 35]		1	**< 0.001**	0.718	**< 0.001**	*0.064*
	>35			1	0.020	**< 0.001**	**< 0.001**
Active (A1)	[18; 25]				1	**0.001**	*0.077*
	[26; 35]					1	0.155
	>35						1

In conclusion, the new ADAS system tested in the driving simulator experiment had significant positive effects on driver behavior during a cyclist overtaking maneuver, producing a significant increase of LC (15.45%) and a reduction of ΔF_{f0} (28%). Moreover, significant gender and age differences were found in driver performance during a cyclist overtaking maneuver with active ADAS system: 1) the tested system was more effective in helping the female drivers to improve the safety of overtaken cyclists and 2) the effectiveness of ADAS system was maximum for older drivers (>35 years).

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