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Impact of take-over control mechanisms on merging operations of conditionally automated vehicles

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ABSTRACT

On the path to fully autonomous road transport, Conditionally Automated Driving (CAD) provides a shared driving experience between the human driver and the automated driving system (ADS). Critical moments arise when drivers must take-over control of the vehicle from the ADS to continue the driving task or perform a specific manoeuvre that is beyond the ADS capabilities. This study investigated the effects of different Take-Over Control (TOC) mechanisms on driver behaviour and performance during a merging manoeuvre after resuming control from a CAD system. Three TOC mechanisms, (i) the steering wheel, (ii) pedals, and (iii) button, were evaluated using the driving simulation. Thirty participants completed three driving sessions on a designed test track. For each session, a single TOC mechanism was activated. Repeated-measures simulation results were analysed using Weibull Accelerated Failure Time with Shared Frailty and linear mixed-effects models. The results showed that, during merging manoeuvres, the steering wheel mechanism led to significantly longer lane-change durations than the button and exhibited lower manoeuvre quality than the pedals, likely due to increased cognitive load. Gender differences were also observed: female drivers commenced lane-change manoeuvres earlier than males but took longer to complete them. The findings offer insights into designing more effective and user-centred TOC mechanisms. In addition, the findings highlight the necessity for more comprehensive designs that consider the variabilities stemming from different ADS interfaces and driver characteristics. Future research should include a broader demographic sample and real-world investigations to further validate the findings and refine these mechanisms.

1. Introduction

Conditionally Automated Driving (CAD) systems represent a significant evolution in vehicle automation technology. These systems are referred to as Level 3 vehicle automation by the Society of Automotive Engineers (SAE, 2021). These systems are capable of performing the driving task autonomously, but rely on human driver intervention when approaching their operational limits. This shared driving experience introduces a safety–critical human–machine interaction (HMI) component known as take-over control (TOC). This process is fundamental to ensuring the safety and performance of CAD systems, where the human driver must smoothly regain control from the automated system and perform the manoeuvre that falls out of the operational domain of the system.

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Among driving manoeuvres, merging is one of the most complex and critical because it requires the simultaneous performance of several tasks, including adjusting speed (acceleration/deceleration), checking traffic signs, coordinating vehicle positioning, and assessing the risk and timing of merging onto the highway (Kherroubi and Aknine, 2024). These simultaneous tasks can increase driver workload and the likelihood of errors which make merging ramps one of the most accident-prone sections of highways (Bhattarai et al., 2025). It is also well known that merging manoeuvres are a major cause of highway bottlenecks, which are significantly affected by drivers' merging behaviour (Marczak et al., 2013). Similar to human drivers, merging manoeuvre remains challenging for automated systems and is not yet fully within their operational domain (Kherroubi and Aknine, 2024). Despite its importance, there is a lack of studies that specifically focus on the merging manoeuvre in the context of CAD systems after drivers resume control. This gap in research leaves uncertainty about how automation might influence driving performance and behaviour during merging manoeuvres. Even at lower levels of automation, only a few studies (de Waard et al., 2009; Hazoor et al., 2023; Hu et al., 2020; Maag et al., 2012) have investigated the effects of advanced driving assistance systems on driver behaviour and performance during the merging process. Maag et al. (2012) found that advanced driver assistance systems significantly reduce both driver workload and situational awareness. It is important to note that current road design configurations were established based on the behaviour and performance of manual drivers (AASHTO, 2018), who are expected to remain in the loop, actively monitor the driving environment, and perform driving tasks.

CAD does not require the drivers to constantly monitor the road. However, when the drivers are not actively engaged in the driving process, they may experience an out-of-the-loop state, leading to reduced situational awareness. As a result, resuming control of the vehicle quickly and safely within a limited timeframe poses a significant challenge for the drivers when performing subsequent driving tasks (Chen et al., 2021a). Roche et al. (2022) found that when drivers resumed control from a CAD system during critical lane-change manoeuvres, they displayed more abrupt deceleration and steering actions than necessary. In other work, researchers have observed increased gaze fluctuation and greater maximum longitudinal deceleration in drivers regaining control for diverging manoeuvre (Chen et al., 2021a). Hence, investigating merging in CAD following a transition of control is a critical area of research, particularly for understanding how various factors including the design characteristics of CAD systems influence driver behaviour and performance during the merging process.

Previous works showed that various factors such as non-driving related tasks (Coyne et al., 2023; Hungund and Kumar Pradhan, 2023; Xu et al., 2024), traffic conditions (Doubek et al., 2020), road geometry and environment (Du et al., 2024; Xu et al., 2022), weather conditions (Papadimitriou et al., 2019), and type of take-over scenarios (Bazilinskyy et al., 2018) have a significant effect on TOC and subsequent driving task. Also several design characteristics of CAD systems, such as the time budget (Deng et al., 2024; Doubek et al., 2020; Roche and Brandenburg, 2018; Weaver and DeLucia, 2022), characteristics of take-over request signals (Brandenburg and Chuang, 2019; Jansen et al., 2022; Petermeijer et al., 2017b; Roche and Brandenburg, 2018), location of TOR devices (Jansen et al., 2022), and the effect of visual information in human–machine interfaces (Goncalves et al., 2022)..

TOC transition mechanisms could also affect the driving task after TOC. Drivers can deactivate the automation system and retake control of the vehicle using TOC mechanisms such as pressing pedals, pressing a button, touching a screen, rotating the steering wheel (Zeeb et al., 2016), using voice commands, or gestures in the air (Detjen et al., 2020). Of these methods, the first three are more commonly used in existing systems and previous research. While many studies focus on a single TOC mechanism (Chen et al., 2021a; Huang and Pitts, 2022; Tan and Zhang, 2022; Yoon et al., 2021), some explore combinations of these methods (Du et al., 2020; Wu et al., 2022; Wu et al., 2021). Petermeijer *et al.* (2017a) found that lane-change durations were significantly longer and more variable, and the steering wheel angle was greater when the driver chose to brake rather than turn the steering wheel to take-over control. In

Fig. 1. Static driving simulator at TRAFIKKLAB, NORD University, Norway.

scenarios where both pedals and the steering wheel were available for TOC, drivers who chose the steering wheel had slower reaction times (Wu et al., 2019). Similar findings by Zeeb et al. (2017) and Wu et al. (2022) suggest that lateral control using the steering wheel may require longer decision making time and impose a greater cognitive load.

The absence of research on driver behaviour during merging manoeuvres in CAD driving systems, coupled with the importance of understanding how CAD system characteristics influence driver behaviour after TOC, underscores the need for this study. Merging manoeuvres, while complex and critical for safety, remain one of the least examined guidance tasks in the context of CAD. Most existing studies have concentrated on tasks like lane-changing and overtaking, leaving merging largely unexplored. Hence, the aim of this study is to investigate the effect of TOC mechanisms, which are fundamental to the operation of CAD systems, on driver's behaviour and performance during merging manoeuvres after a TOC. Additionally, it also considered the influence of the driver's experience and demographics. Specifically, the study investigated such effects on merging manoeuvre duration, merging speeds, and overall driving performance. The findings will help improve the safety and efficiency of CAD system designs.

2. Method

2.1. Driving simulator Equipment and CAD-HMI characteristics

A driving simulation experiment was carried out at the TRAFIKKLAB at NORD University (Norway) (Fig. 1). The facility was equipped with a static driving simulator from AV Simulation. The setup included three 43-inch monitors (resolution of 1920 x 1080 pixels each; field of view 140° horizontally, 30° vertically). Vibration pads were integrated to replicate various driving conditions such as road roughness and vehicle impact. A 2.1 surround sound system added to the realism of the simulation, replicating engine noise, wind, and other environmental sounds.

The driving simulation software used for the experiments was SCANeR Studio®. All key simulation parameters were defined during scenario creation and controlled through the software environment. These parameters are described throughout this section and Section 2.2 of the manuscript. Unless otherwise specified, default settings provided by SCANeR Studio® were applied.

CAD and HMI functions were implemented in the driving simulator. When a driver activated the automation system using a dedicated button on the steering wheel, the CAD system took control of the vehicle until situations arose that necessitated driver intervention. In these cases, the HMI interface notified the driver through visual and audible cues to indicate (i) whether automated driving was active or inactive (Fig. 2a and 2b), (ii) the availability of autonomous mode signalled by a beep to encourage activation (Fig. 2c), and (iii) the need to resume manual control, accompanied by an audible warning (Fig. 2d). A critical five-second window was provided for these interactions and the transition of control back to the driver. It was carefully chosen based on previous research to balance the need for a rapid response with the reduction of potential crashes (Doubek et al., 2020; Mok et al., 2015).

2.2. Design and Procedure

The test-track consisted of a two-lane freeway with a speed limit of 110 km/h, which was connected to another freeway section through a ramp. The ramps consisted of a series of curves suited for a 70 km/h speed limit, including curves that were 150 m long with a 200 m radius. These curves were linked to straight segments by 40 m long spiral curves. The geometric design of the road adhered to the standards set by the American Association of State Highway and Transportation Officials (AASHTO, 2018). The lanes and shoulders of the freeway were 3.6 and 3.0 m wide, respectively. As illustrated in Fig. 3, the entry ramp featured an acceleration lane that was 200 m long and 3.6 m wide, with a 90 m taper at the merging point. Participants drove 5 km before reaching this entry ramp.

A within-subject design was implemented, allowing each participant to drive the test track three times, with each run featuring a different take-over mechanism: (i) steering, (ii) accelerating/braking, and (iii) pressing a dedicated button. A TOR was given 5 s (i.e.,

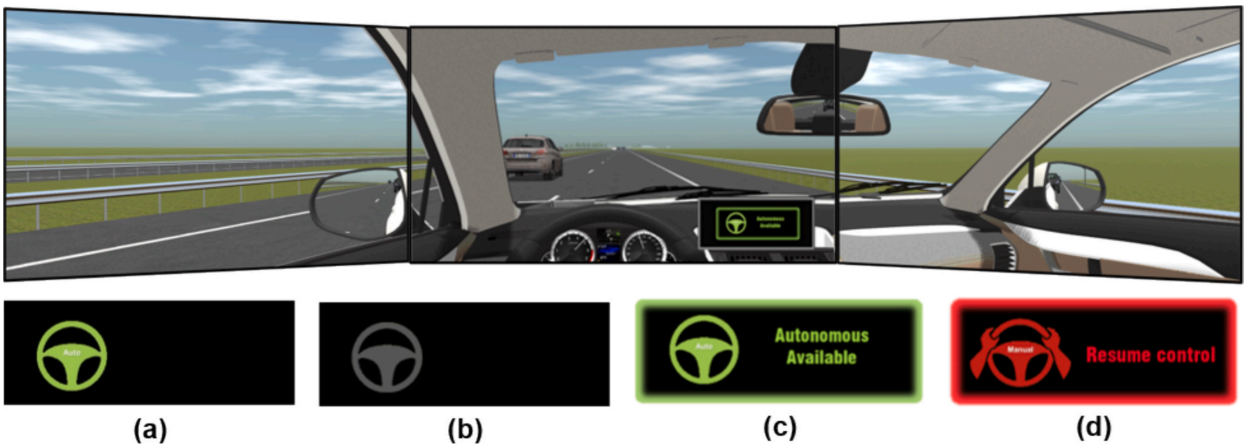

Fig. 2. CAD-HMI characteristics.

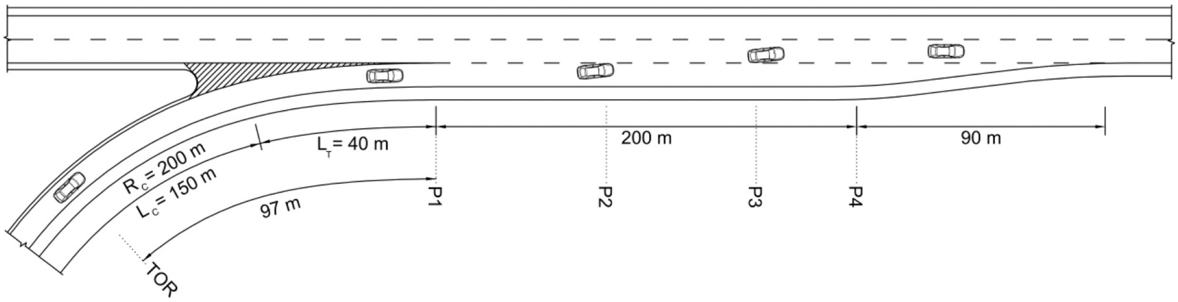

Fig. 3. Merging manoeuvres process and relevant points. Note: L_C = curve length, R_C = curve radius, L_T = transition length; picture not in scale.

equivalent to 97 m at 70 km/h) before the participants entered the acceleration lane to merge with the motorway (see Fig. 3).

The study protocol included several key steps. Participants first completed a pre-drive questionnaire to collect demographic details such as age, gender, driving experience, annual mileage, and crash history. This questionnaire was distributed online during the recruitment phase. In the simulator, an initial briefing covered the system's functionalities and the interpretation of HMI messages. Then, separated by a 3-minute rest period, each participant completed three driving scenarios in random order. Before each session, drivers were familiarized with the specific TOC mechanism to be used in that test scenario through training on a straight track. Drivers were instructed to resume and take-over control only when the system issued a request, and to keep their hands off the steering wheel and feet off the pedals during automated driving.

The experiment concluded with a post-drive questionnaire on simulator sickness, with no cases of sickness being recorded. During the automated driving mode, participants were instructed not to touch the steering wheel or pedals and could only deactivate or activate the system after receiving a TOR. Vehicle data, including speed, position, and acceleration were recorded at a frequency of 100 Hz. Additional variables were derived from the collected data.

2.3. Participants

Aligned with the Code of Ethics of the Association (2024), thirty licenced drivers from Norway participated in the study voluntarily and without compensation. Participants were recruited via advertisements on the social media platform Facebook. Interested individuals completed an online screening questionnaire that gathered demographic and driving-related information, including age, years of driving experience, type of driving licence held, estimated annual kilometres driven, and the number of previous traffic crashes. Eligibility required participants to have normal or corrected-to-normal vision; the use of prescription glasses or contact lenses was permitted as needed. To reduce potential bias, participants were not informed about the hypotheses of the study. The sample focused on individuals within the young to middle-aged demographic, as this group is more inclined to adopt and engage with emerging automotive technologies. The study sample consisted of an equal number of males and females, with an average age of 28.5 years and a standard deviation of 5.0 years; ages ranged from 23 to 38 years old. Prior to data collection, the study procedures were reviewed and approved by the Norwegian Agency for Shared Services in Education and Research (acronym SIKT) to ensure compliance with ethical guidelines and the protection of participants' privacy (ref. nr. 909586). Half of the participants reported prior experience

Table 1
Description of dependent and independent variables.

Variable	Unit	Description	type
T_m	s	the time interval starting when a driver arrives at the beginning of the acceleration lane (P1) to the point at which the subject vehicle begins lane change (P2).	Dependent
T_l	s	the amount of time it takes for a vehicle to complete a manoeuvre of moving from the acceleration lane (P2) to the through lane (P3), i.e., the lane-change duration.	Dependent
S_a	km/h	Average speed of subject vehicle from when a driver arrives at the beginning of the acceleration lane (P1) to the point at which the subject vehicle ends lane change (P3), i.e., the average merging speed.	Dependent
A_{mlt}	m/s^2	Maximum lateral acceleration during lane change (from P2 to P3)	Dependent
A_{alt}	m/s^2	Average lateral acceleration during lane change (from P2 to P3)	Dependent
A_{mln}	m/s^2	Maximum longitudinal acceleration during merging (from P1 to P3)	Dependent
SW_{ml}	deg.	Maximum steering wheel angle during lane change (from P2 to P3)	Dependent
SW_{al}	deg.	Average steering wheel angle during lane change (from P2 to P3)	Dependent
R_d	m	The distance between the starting point of a lane-change (P2) manoeuvre and the beginning of the taper (P4).	Dependent
TOC mechanism	–	Three different take-over mechanisms including (i) rotating steering wheel, (ii) pressing pedals, and (iii) pushing button on steering wheel	Independent
age	years	Age of participants	Independent
male	–	Gender of participants (= 1 if male, and = 0 if female)	Independent
annual_mileage	km/year	The total distance (measured in kilometres) a participant drives over the course of one year	Independent
years_licenced	years	The number of years a participant has held a valid driving licence.	Independent

with CAD, and the majority had used specific ADAS features. To mitigate the potential influence of prior familiarity with CAD systems, a training session was conducted for all participants before each experimental drive.

2.4. Variables and statistical analyses

2.4.1. Dependent and independent variables

Table 1 shows the dependent and independent variables in this study. These variables were chosen to comprehensively capture the critical aspects of driver behaviour and performance during merging, a task that involves complex decision-making and precise vehicle control. The selection was informed by previous studies and road design guidelines on merging dynamics and driver behaviour (AASHTO, 2018; Akbarpoor and Monajjem, 2025; Alamry and Hassan, 2024; Calvi and De Blasiis, 2011; Portera and Bassani, 2020) to be sure that both lateral and longitudinal control aspects are reflected in the analysis. The dependent variables specifically represent key indicators of merging quality and safety.

The time-based variables, such as time to lane-change initiation (T_m) and lane-change duration (T_l) were selected to assess decision-making and manoeuvre execution efficiency. Shorter time to lane–change initiation can reflect faster situational awareness and confidence for conducting lane change, however too short or long lane-change duration values could indicate risky or hesitant behaviour (Matcha et al., 2021). Speed and acceleration variables (i.e., S_a, A_{mlt}, A_{alt}, A_{mln}) reflect how smoothly and safely the merging manoeuvre is executed. Higher average speed but less than the speed design, and moderate, stable acceleration are generally desirable, as they suggest controlled and efficient merging (AASHTO, 2018; de Waard et al., 2009; He et al., 2025).

Mean and maximum steering wheel angle (i.e., SW_{ml}, SW_{al}) during lane change help assess lateral stability. Smaller fluctuations or smoother steering inputs are associated with more stable transitions and safer merging manoeuvre (Portera and Bassani, 2020).

Remaining distance to the end of acceleration lane (R_d) indicates whether the acceleration lane length is sufficient for freeway merging; negative of remaining distance to the end of acceleration lane values suggest that the acceleration lane length is inadequate and lane change occurred after the acceleration lane ended which implied delayed decisions and potentially unsafe conditions (Alamry and Hassan, 2024; Calvi and De Blasiis, 2011; Portera and Bassani, 2020).

Finally, demographic variables like age and gender explore variability in performance, ensuring findings are applicable across diverse driver populations. These factors have been recognized as significant in the merging process (Bhattarai et al., 2025; de Waard et al., 2009). Furthermore, research indicates that drivers' demographic characteristics influence their decision time and performance during lane change after TOC (Muslim et al., 2021; Muslim et al., 2022). All driver behaviour metrics were calculated using data recorded by the simulator. Speed and acceleration were extracted from the vehicle's trajectory data, and time-based measures were determined using time stamps at key points during the merging process (P1–P3 in Fig. 3). The starting point of merging manoeuvre was at the beginning of the acceleration lane (point P1 in Fig. 3). Lane–change manoeuvre started when the left front wheel of subject ego vehicle crossed the road marking between acceleration lane and motorway lane (point P2 in Fig. 3). The end point of both merging and lane–change manoeuvres was considered when the right back wheel crossed the road marking between acceleration lane and the motorway lane (point P3 in Fig. 3).

2.4.2. Modelling the duration of merging and Lane-Change Events

T_m and T_l were modelled using the Accelerated Failure Time (AFT) model, which effectively captures the direct effect of a factor on survival time (i.e., the time to event). The AFT model is defined by Equation (1), where the natural logarithm of T_m or T_l is expressed as a linear function of the independent variables:

$$\ln(T) = \beta X + \varepsilon \tag{1}$$

where X and β are the vectors of independent variables and coefficients, respectively; and ε is the error term. The Weibull distribution is a flexible distribution that can model time-to-event data with varying hazard rates. Therefore, the Weibull AFT model is appropriately used to analyse such scenarios in this study. As this experiment used a within-subject design, unobserved heterogeneity presents a significant challenge. To effectively address this issue, similar to random effects models, shared frailty is incorporated. The conditional hazard and survival functions are presented by Equation (2) and (3), respectively.

$$h_{ij}(t|\alpha_i) = \alpha_i h_{ij}(t) = \alpha_i p t^{p-1} \exp(-p\beta X_{ij}) \tag{2}$$

$$S_{ij}(t|\alpha_i) = \exp\left(-\int_0^t h_{ij}(r|\alpha_i)dr\right) = \exp\left(-\alpha_i \int_0^t h_{ij}(r)dr\right) \tag{3}$$

where, t denotes the elapsed time from the start of the event; h_{ij} and S_{ij} are the hazard and survival functions for the i^{th} participant using the j^{th} observation. The frailty term, α_i, is specific to the i^{th} participant and is modelled to follow a Gamma distribution with a mean of one and a variance of θ. p is the shape parameter. The hazard rate increases with T_m or T_l when p is greater than 1 and decreases when p is less than 1. Interestingly, the Weibull distribution becomes equivalent to an exponential distribution when $p = 1$.

2.4.3. Modelling driving performance measures

Since repeated measurements were taken for each participant, the linear mixed-effects models were employed to investigate the influence of independent variables on continuous dependent variables, including speed, acceleration, steering wheel angle, and remaining distance in the general form of linear mixed-effects model can be expressed as:

$$y_{ij} = W_{ij}\beta + Z_{ij}u_i + \varepsilon_{ij} \quad (4)$$

where y_{ij} represents the dependent variable measured for participant i at observation j. W_{ij} is the design matrix associated with the fixed effects, and β is the corresponding fixed-effects parameter vector. The design matrix Z_{ij} and u_i capture the random effects specific to each participant i. The residual error ε_{ij} is unexplained variability at the observation level. Both u_i and ε_{ij} are assumed to be normally distributed Further details on the theory and estimation procedures of linear mixed–effects models are provided (West et al., 2022).

2.4.4. Parameters estimation procedures

Both the shared frailty Weibull AFT model and the linear mixed-effects model were estimated using *STATA* statistical software (StataCorp, 2017) with the shared frailty Weibull AFT model fitted via the *streg* command and the linear mixed-effects model fitted via the *mixed* command. The parameters of shared frailty and the linear mixed-effects model were estimated using the restricted maximum likelihood and maximum likelihood estimation methods, respectively.

3. Results

Table 2 provides a summary of the dependent and independent variables. The results of Table 2 and Fig. 4 show that the average time participants took for the first part of the merging manoeuvre (T_m) was longer than the second part (i.e., lane change, T_l). Specifically, the minimum time for T_m (steering wheel: 3.13 s) still exceeding the maximum time for T_l (steering wheel: 2.25 s). Fig. 4 shows that the greater dispersion observed in T_m indicates more variability in drivers' decisions, which could reflect a higher degree of heterogeneity in how they approach initiating a lane change compared to the more consistent timings observed in lane-change duration. The standard deviation of S_a (i.e., 4.83 km/h) was higher for participants who used the steering wheel to take-over control before a merging manoeuvre, compared to other TOC mechanisms. Both the average and standard deviation of the maximum and average lateral acceleration during the lane change (A_{mlt} and A_{alt}) were higher when participants used the steering wheel, compared to the other two TOC mechanisms. In addition, participants rotated the steering wheel more during lane changes when they used it to take-over control before merging. The average of remaining distance (R_d) showed minimal variation across different TOC mechanisms. However, three negative values of remaining distance to the end of acceleration lane (R_d) were observed, indicating that in these runs,

Table 2
Summary statistics of dependent and independent variables.

Variables		Unit	Mean	St. dev.	Min.	Max.
T_m	Button	s	3.44	1.97	1.05	9.82
	Pedals		3.39	1.82	1.09	9.42
	Steering wheel		3.13	1.76	0	9.01
T_l	Button	s	1.98	0.60	0.79	3.29
	Pedals		2.10	0.64	1.03	3.78
	Steering wheel		2.25	1.01	0.91	5.1
S_a	Button	km/h	77.68	4.25	4.25	85.72
	Pedals		78.58	4.24	71.37	89.13
	Steering wheel		76.65	4.83	67.32	87.68
A_{mlt}	Button	m/s^2	0.50	0.30	0.20	1.31
	Pedals		0.46	0.20	0.18	0.95
	Steering wheel		0.59	0.35	0.18	1.43
A_{alt}	Button	m/s^2	0.23	0.16	0.08	0.64
	Pedals		0.21	0.12	0.05	0.58
	Steering wheel		0.27	0.20	0.05	0.83
A_{mln}	Button	m/s^2	0.79	0.30	0.31	2.12
	Pedals		0.80	0.29	0.33	2.13
	Steering wheel		0.75	0.21	0.21	0.95
SW_{ml}	Button	deg.	4.33	3.10	1.21	12.99
	Pedals		4.10	2.22	1.18	9.64
	Steering wheel		5.43	3.77	1.14	13.69
SW_{al}	Button	deg.	2.32	1.66	0.67	6.95
	Pedals		2.08	1.27	0.39	5.90
	Steering wheel		2.72	2.16	0.43	9.04
R_d	Button	m	126.66	46.08	−28.65	178.58
	Pedals		127.06	43.40	−30.13	177.77
	Steering wheel		134.35	40.88	−15.06	200.02
age	All	years	28.46	4.93	23	38
	Males		28.87	5.25	23	38
	Females		28.07	4.62	23	36
annual_mileage	All	km/year	18,508	7256	2750	32,500
	Males		18,172	6862	2750	32,500
	Females		18,844	7692	2750	32,500
years_licenced	All	years	9.3	4.20	4	19
	Males		9.8	4.25	4	19
	Females		8.7	4.13	4	19

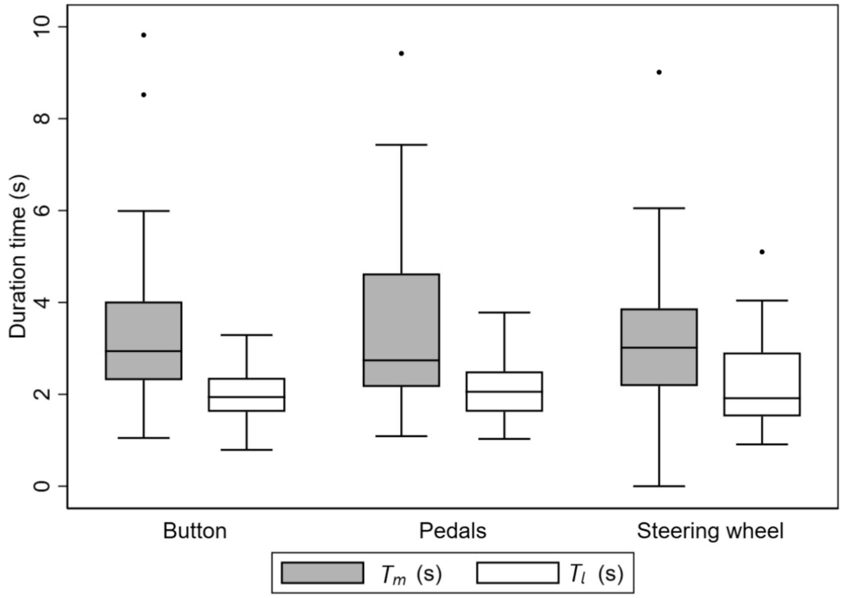

Fig. 4. Boxplots of the duration from the beginning of the acceleration lane to the time to lane–change initiation (T_m), and lane-change duration (T_l).

participants began their lane-changing manoeuvre in the taper section, after the acceleration lane ended. Table 2 shows that participants drive an average of 18,508 km per year and have held their driving licences for 9.3 years.

Table 3 shows the estimated shared frailty Weibull AFT model for time to lane-change initiation and lane-change duration (T_m and T_l). The results of the likelihood ratio (LR) tests for overall significance demonstrate that the time to lane-change initiation and lane-change duration models were significant at the 95 % and 90 % confidence levels, respectively. The results of the LR test also revealed that the θ values for both models were statistically significant at the 95 % confidence level. As indicated in Table 3, the shape parameter *p* of the Weibull distribution for both models was greater than 1, which indicates that both time to lane-change initiation and lane–change duration, T_m and T_l, had a positive duration dependence. This implies that the probability of completing the manoeuvres increased with time.

Table 3 also shows that TOC mechanisms had a significant effect on lane-change duration at the 95 % confidence level but did not affect time to lane-change initiation. The results indicate that lane-change duration for button TOC mechanisms was significantly shorter than for those using a steering wheel. However, the difference for pedals compared to the steering wheel was not statistically significant at the 95 % confidence level. Gender had a significant effect on both models. Males had a statistically longer time to lane-change initiation but a shorter lane-change duration compared to females. In both models, *age* had no statistically significant effect on time to lane-change initiation and lane-change duration.

Fig. 5 presents survival curves for the time taken to initiate a lane change and the duration of the lane change, T_m and T_l respectively, for different TOC mechanisms. This reveals how the likelihood of completing merging and lane-change maneuvers changes over time. These curves illustrate the relative effectiveness of each TOC mechanism. Fig. 5a shows that the TOC mechanism had no effect on time to lane-change initiation, T_m, implying that the time taken by drivers from entering the acceleration lane to deciding to start the lane change was unaffected by the available TOC mechanisms. However, Fig. 5b shows that the lane-change duration, T_l, was affected by the TOC mechanisms, indicating that lane-change duration is significantly longer when the steering wheel mechanism is available to take control.

Fig. 6 shows the survival curves for the time to lane-change initiation and lane-change duration, T_m and T_l respectively,

Table 3
Estimated Weibull AFT Models with Shared Frailty for T_m and T_l.

	T_m			T_l		
	β	Std. err.	*p*-value	β	Std. err.	*p*-value
TOC mechanism						
Button	− 0.013	0.0832	0.873	− 0.163	0.0683	0.017
Pedals	− 0.015	0.0856	0.860	− 0.111	0.0694	0.109
male	0.354	0.1368	0.010	− 0.273	0.1032	0.008
Constant	0.896	0.1153	0.000	0.954	0.0764	0.000
p	3.559	0.3858	–	4.341	0.5174	–
θ	1.068	0.3572	–	0.681	0.2986	–
# observations	90	–	–	90	–	–

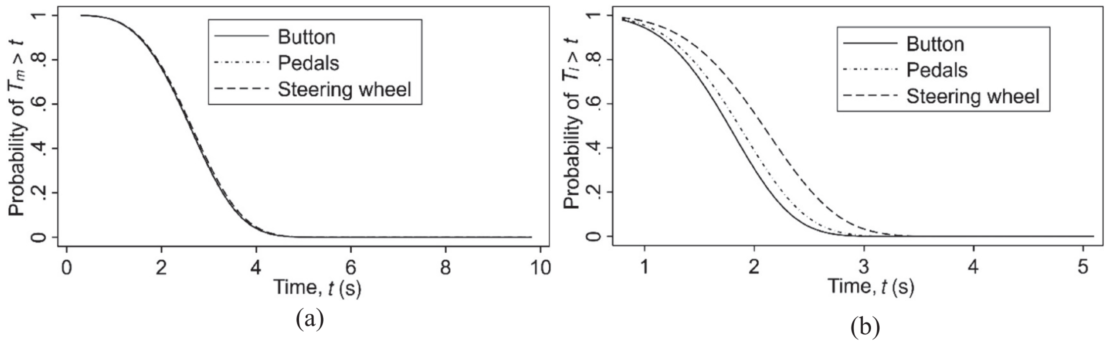

Fig. 5. Survival curves for (a) T_m and (b) T_l across different TOC mechanisms.

differentiated by gender. Fig. 6a reveals that females initiate lane changes earlier than males. However, Fig. 6b shows that females take longer to complete a lane change than males.

Table 4 shows the estimated parameters of linear mixed-effect models for S_a, A_{mlt}, and A_{alt}. Table 5 also reports the results of the same models for mean and maximum steering wheel angle (SW_{ml} and SW_{al}). Overall, all models were significant at the 95 % confidence level. Results from the LR test revealed that the inclusion of random effects significantly improved the model fit at the 95 % confidence level. These results implied that TOC mechanisms had a significant effect on S_a, A_{mlt}, A_{alt}, mean and maximum steering wheel angle (SW_{ml}, and SW_{al}) at the 95 % confidence level. The number of years participants held a driving licence (*years_licenced*) had a significant effect only on maximum lateral acceleration and maximum steering wheel angle during lane changes with longer-licenced participants showing lower maximum lateral acceleration and steering wheel angles. Gender had a significant effect on S_a, but not on the other dependent variables. The variable *age* had no significant effect on any of the measurements. None of the independent variables had a significant effect on maximum longitudinal acceleration during merging and remaining distance to the end of acceleration lane at the 95 % confidence level.

Fig. 7 shows the pairwise comparison of S_a and maximum lateral acceleration (A_{mlt}) between TOC mechanisms. This has been adjusted using Scheffe's method to control for Type I error inflation. Fig. 7a shows that drivers choose an average merging speed that is statistically significantly lower when the steering wheel is used as a TOC mechanism than when the pedals are used. This reduction in speed may be due to the greater cognitive demand of using the steering wheel, causing drivers to spend more time taking control before initiating the merging manoeuvre. By reducing their speed and allowing more time, drivers were probably trying to perform a safer manoeuvre when merging. However, there were no significant differences in S_a between the button and the other two TOC mechanisms at the 95 % confidence level. Despite the lower merging speed associated with the steering wheel mechanism, Fig. 7b shows that the maximum lateral acceleration during lane change, A_{mlt}, occurred in this scenario. One plausible interpretation is that the cognitive and motor demands of steering wheel control may lead to a more dynamic or abrupt manoeuvre. Furthermore, as shown in Table 4, males significantly prefer higher speeds than females.

As shown in Fig. 8, the maximum and average steering wheel angles during lane changes were significantly higher in scenarios where the steering wheel was available for TOC than in scenarios where the pedal was available, at the 95 % confidence level. The observations of three participants (TD#7, TD#16, and TD#22) demonstrate heterogeneous variability between drivers, which is accounted for by a mixed-effects model. Fig. 7 and Fig. 8 show that the variability for these three participants when using the pedal is lower than for the other two TOC mechanisms. Similar results, in terms of standard deviation, can be seen in Table 2.

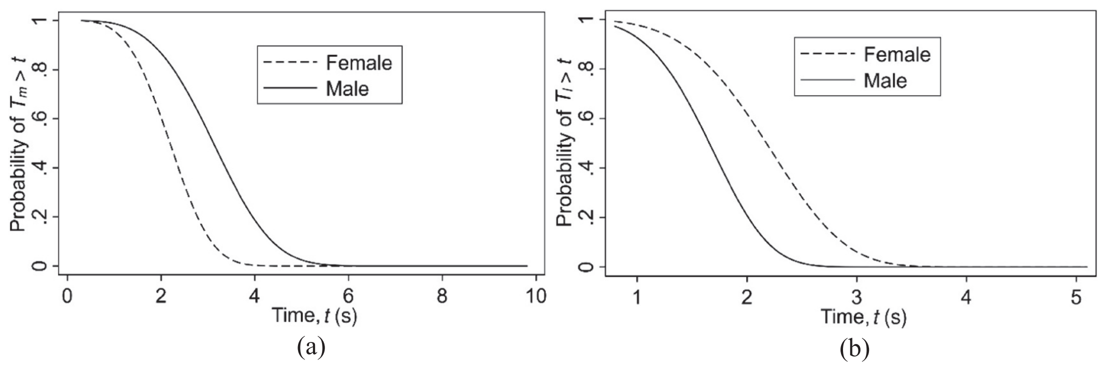

Fig. 6. Survival curves for (a) T_m and (b) T_l across males and females.

Table 4
Estimation of Linear Mixed-Effects Models for S_a, A_{mlt}, and A_{alt}.

	S_a			A_{mlt}			A_{alt}		
	β	Std. err.	*p*-value	β	Std. err.	*p*-value	β	Std. err.	*p*-value
TOC mechanism									
Button	1.03	0.7464	0.168	− 0.08	0.0405	0.037	− 0.03	0.0232	0.175
Pedals	1.93	0.7464	0.010	− 0.13	0.0405	0.002	− 0.05	0.0232	0.018
male	3.31	1.2008	0.006	–	–	–	–	–	–
years_licenced	–	–	–	0.012	0.005	0.008	–	–	–
constant	75.00	0.9522	0.000	. 69	0.0672	0.000	0.27	0.0292	0.000
Random-effects parameters									
σ^2 of intercepts	8.03	2.8382	–	0.06	0.0179	–	0.017	0.0052	–
σ^2 of residuals	8.36	1.5258	–	0.02	0.0045	–	0.008	0.0015	–
# observations	90	–	–	90	–	–	90	–	–

Table 5
Estimation of Linear Mixed-Effects Models for SW_{ml} and SW_{al}.

	SW_{ml}			SW_{al}		
	β	Std. err.	*p*-value	β	Std. err.	*p*-value
TOC mechanism						
Button	− 1.04	. 4349	0.017	− 0.41	0.2498	0.103
Pedals	− 1. 28	. 4349	0.00 3	− 0.65	0.2498	0.010
years_licenced	− 0.11	0.0489	0.025	–	–	–
constant	6.41	0.7134	0.000	2.72	0.3111	0.000
Random-effects parameters						
σ^2 of intercepts	6.64	1. 9764	–	1.97	0.5912	–
σ^2 of residuals	2.83	0.5177	–	0.94	0.1710	–
# observations	90	–	–	90	–	–

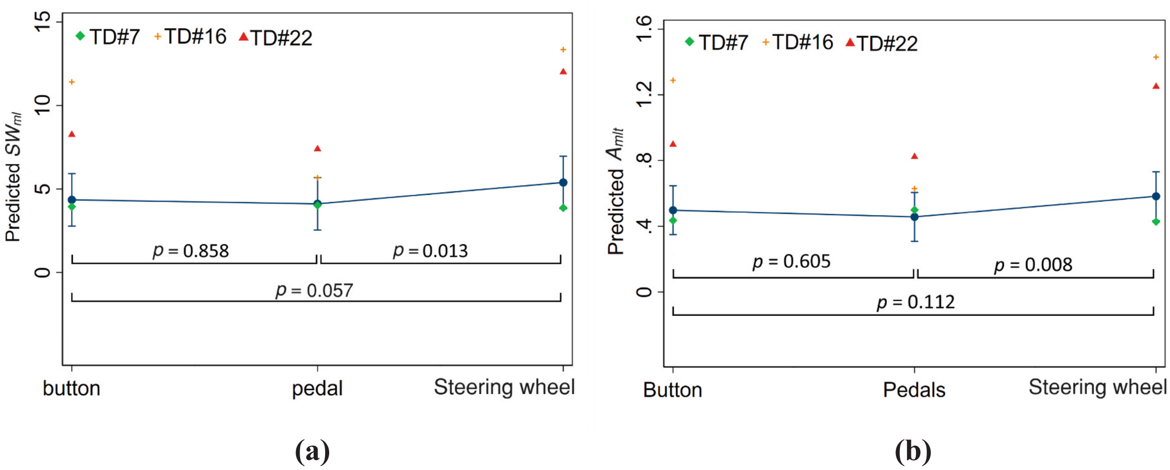

Fig. 7. Effect plot for (a) S_a and (b) A_{mlt} under different TOC mechanisms.

4. Discussion

This study investigated the effects of different TOC mechanisms on driver merging behaviour and performance after resuming control from the automated system. Analysis of survival-curve indicated that, while the take-over control mechanism did not affect the time it took drivers to initiate a lane change, the steering wheel mechanism significantly prolonged the duration of the lane-change. These results are consistent with the findings of Wu et al. (2019) and Zeeb et al. (2017), who found longer lane-change durations due to higher cognitive load. Steering, compared to pushing pedals or pressing a button, requires more motor processes, situational awareness, precision, and coordination, as the driver must account for lane positioning while considering the surrounding environment and vehicles. Extended lane-change durations could reduce drivers' available reaction time in real-world merging scenarios, which may increase accident risk, as previous studies have found similar results (Chen et al., 2021b; Karimi et al., 2021).

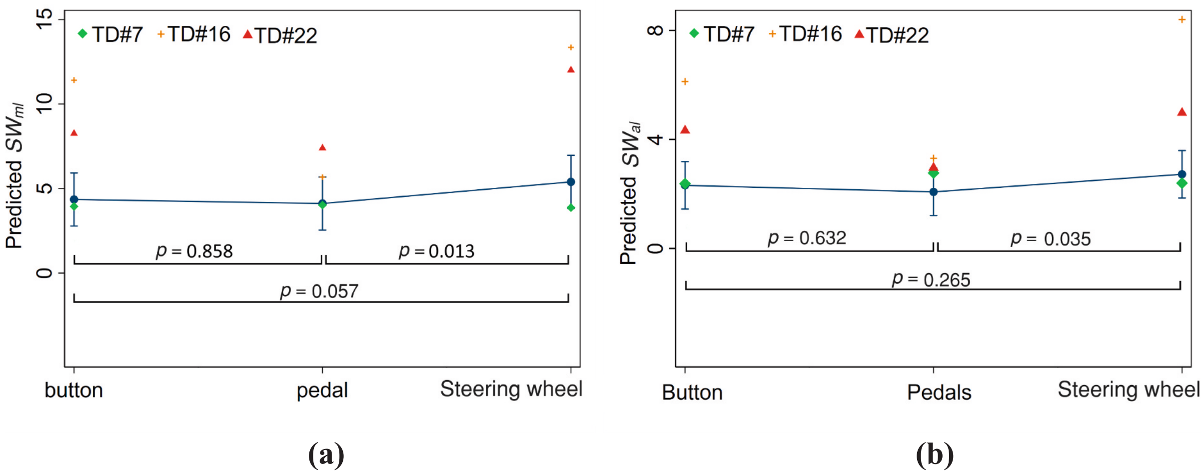

Fig. 8. Effect plot for (a) SW_{ml} and (b) SW_{al} under different TOC mechanisms.

Based on Fig. 5a, as there is no significant difference between mechanisms in the time from the start of the acceleration lane to lane-changing initiation. However, further analysis of the data showed that the steering wheel mechanism resulted in the longest time from the take-over request to take-over control (Karimi et al., 2025). Additionally, while most drivers completed the take-over control phase before reaching the start of the acceleration lane, the steering wheel mechanism was associated with the shortest time from take-over control to reaching the start of the acceleration lane. This shorter time to lane-change initiation may contribute to longer lane-change durations as drivers need more time to monitor their surroundings during the manoeuvre.

Analysis of survival-curve by gender showed that, although females initiated lane changes sooner than males, they took longer to complete the manoeuvre. Although there is no similar study in CAD, some studies in manual driving have investigated the effect of gender on merging behaviour. Hang et al. (2018) found that male drivers generally completed their lane-change manoeuvres faster than female drivers merging process in a work zone area. However, Yuan et al. (2019), through a driving simulator study on merging behaviour into freeways, found opposite results, where females conducted significantly faster lane changes compared to males. In another driving simulator study, Titiloye et al. (2021) found no significant gender differences in freeway merging duration. These variations in the results of a few related works in manual driving, and the lack of studies in CAD, highlight the need for future studies to further evaluate the effect of gender on merging behaviour. Moreover, Table 3 indicates no significant interaction between gender and TOC mechanism, suggesting that the differences observed in Fig. 6 are consistent across different TOC mechanisms. Two measures of participants' driving experience, which are the average kilometres driven per year and the number of years they have held their driving licences, had no significant effect on T_m and T_l at the 95 % confidence level. One possible explanation is that merging onto a freeway with no through traffic and no non-driving-related tasks simplifies the process and reduces the influence of driving experience. The absence of external distractions or secondary tasks likely allowed participants to focus entirely on the merging manoeuvre, minimizing differences in performance due to experience. Conversely, in real-world traffic, driver experience might play a crucial role when selecting a gap between through vehicles for merging under real traffic conditions, especially when drivers are required to divide their attention between the driving task and other concurrent demands. This should be investigated in future work.

Pairwise comparisons showed that drivers merged at lower speeds with the greatest lateral acceleration when using the steering-wheel take-over, whereas the button mechanism did not differ from the pedal one. Generally, males selected higher merging speeds than females. Although there are no studies that directly investigated this, previous studies (Mehdizadeh et al., 2022; Watson et al., 2015) that used speed data along freeways and traffic offence datasets, respectively, have consistently observed that males exhibit speeding behaviour more frequently than females. The observed gender differences in merging speed may relate to differences in driving style and risk perception (Rhodes and Pivik, 2011) with regaining control after automation. Female drivers may adopt more cautious strategies, leading to earlier but slower lane changes, while male drivers may feel more confident. In conditionally automated driving, this re-engagement process can amplify such differences because it requires drivers to assess the situation quickly and make safe decisions under time pressure. Li et al. (2022) found significant differences in some TOC-related measures in CAD.

The steering-wheel take-over produced larger steering angles than pedal control. A mixed–effects analysis confirmed that the driver-to-driver variability was consistent with the dispersion patterns seen in Figs. 7–8 and Table 2. No significant effects of *age* were found in this study. However, previous research has shown age to influence merging behaviour significantly. For example, Titiloye et al. (2021), in a study that included participants aged 18 to over 65 years, found that age had a significant effect on merging duration, with older drivers taking longer to merge. These findings are consistent with those of Yuan et al. (2019), who examined drivers aged 18 to 75 years. The limited *age* range in this study (23 – 38 years) may explain the lack of significant findings related to age, as it fails to capture the broader variability observed in older populations. The results from the mixed-effects models showed that the number of years participants had held their driving licences had a negative significant effect on the maximum lateral acceleration and maximum steering wheel angle during lane changes, but not on their average values. This suggests that more experienced participants performed less abrupt lateral actions and executed smoother lane changes. However, no significant effect was found for the average kilometres driven per year. Zhang et al. (2023) found that both years of holding a driving licence and the average kilometres driven per year had a significant effect on lateral control during lane changes to avoid collisions with stationary vehicles, with more experienced drivers performing smoother manoeuvres.

These findings suggest that designers should consider prioritizing button or pedals mechanisms for freeway merging scenarios, as they enable quicker, smoother, and more stable transitions compared to steering wheel mechanism. However, these mechanisms should also be tested in other driving scenarios to ensure their effectiveness and adaptability across a wider range of conditions. The developed model in this study is essential not only for understanding traffic safety but also for evaluating traffic efficiency in the context of merging manoeuvres. This becomes especially relevant when calibrating or updating microsimulation models to incorporate CAD systems (Akbarpoor and Monajjem, 2025; He et al., 2025; Holley et al., 2024; Mirzahossein and Mashhadloo, 2024; Mirzahossein et al., 2024).

5. Conclusions

This study aimed to evaluate the effects of different Take-Over Control (TOC) mechanisms on driver behaviour and performance during merging manoeuvres in vehicles operating with CAD systems. The study found that the choice of TOC mechanism significantly influences the duration and quality of merging manoeuvres through a driving simulation experiment and statistical analyses, including Weibull Accelerated Failure Time with Shared Frailty and Linear Mixed–Effect. With the use of the steering wheel, longer lane-change times were observed. Although the study did not directly measure cognitive load, one possible explanation for this finding is that steering requires a higher cognitive demand compared to pedals or buttons, due to the increased demand on motor processes, situational awareness, and lateral control. Gender differences were also found, with female drivers taking longer to complete lane changes. However, no significant effects of age were observed, potentially due to the limited age range of the study sample, which consist of predominantly young drivers.

The results highlight the importance of optimizing TOC mechanisms to improve driver safety and system efficiency. This study did not include a manual driving mode; future studies could compare manual and CAD modes for merging manoeuvres to determine if the current road configuration requires redesign for CAD systems. While our study did not incorporate direct measures of cognitive load, future research could benefit from integrating objective assessments such as physiological indicators or validated workload scales to further elucidate how cognitive demands interact with motor and perceptual aspects during merging manoeuvres. In this study, drivers used only one specific TOC mechanism per run. However, allowing drivers to choose their preferred mechanism before a merging ramp could enhance insights into user preferences and inform the relative importance that should be given to each mechanism in the design and evaluation of CAD systems. Future research should extend these investigations to include a wider range of demographic factors, in particular a wider age range including older drivers (age $>$ 40 years), and scenarios with different traffic conditions, road geometries (i.e., terminal ramp length), and weather conditions to validate and extend these findings. This study provides valuable insights to help the development of safer and more efficient CAD systems by advancing our understanding on how TOC mechanisms affect the driver's behaviour and performance. To ensure safe and efficient CAD operations, improvements are needed in several areas, including optimizing TOC mechanisms to reduce cognitive load, enhancing Human Machine Interfaces (HMIs) to simplified takeovers, and dynamically adjusting TOC timing based on road complexity, traffic, and driver readiness.

On the other hand, the standards for the length of acceleration lanes, which have been defined exclusively for human-controlled driving, need to be re-evaluated in the light of the introduction of autonomous vehicles. As in this case study, manoeuvre times and lengths are influenced by the different performance of the automation systems, as well as the performance of the drivers called upon to intervene in the completion of the merging manoeuvre after a take-over request. This highlights the need for a general and substantial revision of the existing technical regulations on the geometric design of roads.

CRediT authorship contribution statement

Arastoo Karimi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Abrar Hazoor:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Arash Hassani Barbin:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Giuseppe Marinelli:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Bassani:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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