MSc. Thesis
M.P.P. Weijerman

The effects of a varying steering response in machine-initiated and driver-initiated steering systems on driving behaviour and driver acceptance

TU Delft

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The effects of a varying steering response in machine-initiated and driver-initiated steering systems on driving behavior and driver acceptance

by

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Preface

The motivation for this research is the need to gain a better understanding of human-machine interaction in relation to active steering systems. In my literature survey, I found a remarkable gap in literature regarding the effects of active vehicle dynamics on driving behavior and driver acceptance. When designing active vehicle dynamics, the effect on vehicle performance and stability is quite often the main focus of attention whereas the effect on the driver is mostly disregarded.

Whether machine- and driver-initiated adaptations of steering dynamics positively affect driving behavior and driver acceptance remains unclear. Rather than solely evaluating active systems on their performance on the road, this research aims to investigate the driver-machine interaction by conducting a human factors driving simulator experiment.

M.P.P. Weijerman
Rotterdam, May 2021

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I would like to thank David Abbink and Timo Melman for their guidance and support throughout my Master Thesis. Their incredible enthusiasm when I was presenting results and discussing new ideas helped me to stay motivated to keep on moving forward. Timo was always available to brainstorm about ways to further improve the experiment and his feedback on my work challenged me the bring it to a level I could not have reached on my own. David's vision and view on this topic was fascinating to experience. His positive energy and enthusiasm during all our meetings made it something to look forward to. Furthermore, I would also like to thank Joris Giltay and Niek Beckers for the development of JOAN and their help to develop my experiment successfully. Finally, I would like to thank my family and friends for their endless support.

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The effects of a varying steering response in machine-initiated and driver-initiated steering systems on driving behavior and driver acceptance

M.P.P. Weijerman

Abstract*—Currently, active steering systems are implemented in production vehicles to assist the driver by varying the steering response, where the adaptation of the steering response is either initiated by the vehicle or by the driver. Though studies have shown that these steering systems affect the steering performance positively, the effect on driving behavior and driver acceptance is not taken into account. Moreover, the effect of machine-initiated and driver-initiated steering systems on the driver has yet to be investigated. The aim of this driving simulator study was to examine the effects of machine-initiated and driver-initiated steering systems on driving behavior and driver acceptance. During the experiment, the machine switched between a slow and fast steering response on predetermined locations based on the traffic conditions and road curvature, and the driver could switch the steering response by pressing a mouse-button which was attached to the steering wheel. The expectation was that the preferred steering response would be dependent on the steering task, and that between machine- and driver-initiated steering there would be a trade-off between effort and acceptance. Twenty-four participants drove with a constant velocity on a two-lane road with three sections i.e. overtaking traffic vehicles, driving on a straight road and driving on a curved road. Four conditions were completed in a counter-balanced order i.e. passive slow steering response (PS), passive fast steering response (PF), machine-initiated steering (MI) and driver-initiated steering (DI). A post-experiment questionnaire showed that the participants had a preferred steering response for each of the three sections: between slow and fast for overtaking, slow on the straight road, and fast on the curved road. Furthermore, a lower effort and higher acceptance was achieved with the active steering systems compared to the passive steering systems, where there were no significant differences between MI and DI. For future research, it is recommended to further investigate the use of a range of steering responses and free driving speed.

I. INTRODUCTION

The steering ratio of a vehicle is the ratio between the angle of the steering wheel and the angle of the front-wheels, or in other words the ratio between the steering input of the driver and the output of the wheels. Essentially, it determines how much steering is needed to complete a manoeuvre. Up until the late 90's, steering systems in production vehicles were designed with a constant steering ratio [1]. There are two downsides of a constant steering ratio. At low speed, the required steering input of the driver is large which increases driver's physical workload, for example during parking manoeuvres [2]. At high speed, the steering response might be too sensitive which is undesirable since the stability of the vehicle becomes more critical at higher speeds. At high speed for example, a small steering angle creates a relatively large lateral acceleration and yaw moment which decreases the vehicle stability [2]. Furthermore, if the steering response is too sensitive, it will presumable be more difficult to control the vehicle precisely. A less sensitive steering response would enable quieter and safer vehicle guidance, resulting in sturdier drive-ability [3]. These examples show that there is a trade-off between reducing driver's physical workload at low speed and increasing vehicle stability at high speed when designing passive steering systems, which facilitates the need for active steering systems.

In contrast to passive steering systems, where the steering ratio is fixed, active steering systems can adapt the steering ratio to make the steering more responsive at low speed and less responsive at high speed. The adaptation of the steering ratio can be triggered by various metrics. An example where it is triggered by the vehicle speed and steering wheel angle is shown in the Honda S2000 [1] [4], which is one of the first production vehicles with an active steering system. Shimizu et al. (1999) designed a variable gear-ratio steering system, which varies with the vehicle speed and the steering wheel angle [2]. The first adaptation logic states that the steering ratio increases (becomes lower geared) with an increasing vehicle speed and the steering ratio decreases (becomes higher geared) with a decreasing vehicle speed. The second adaptation logic states that the steering ratio increases (becomes lower geared) with a decreasing steering wheel angle and the steering ratio decreases (becomes higher geared) with an increasing steering wheel angle. The benefit of this steering system is that the driver needs to steer less at lower speeds (e.g. during parking) and the vehicle stability increases at higher speeds [2] [3]. Furthermore, the yaw response was maintained for increasing steering wheel angles which improves manoeuvrability during evasive manoeuvres.

The adaptation can also be triggered by the understeer and oversteer of the car, as shown in the BMW 5 Series in 2003. Koehn and Eckrich (2004) designed a steering system which intervenes actively to compensate for understeer and oversteer of the car [5]. This was one of the first production vehicles to actively determine understeer and oversteer of the car and use this to assist the driver by adapting the steering ratio.

Seraslan (2014) designed an active steering system which adapted the steering ratio to keep the steering feel the same by compensating for changing vehicle parameters, such as the tyre cornering stiffness, vehicle mass or moments of inertia [6]. This was done by continuously estimating the yaw amplification, which is defined as the ratio between the yaw rate and the steering angle and comparing it with the desired yaw amplification. The difference between the estimated yaw amplification and the desired yaw amplification is used to adapt the steering ratio to create a consistent steering feeling. For example, if the vehicle mass increases, the yaw amplification decreases for the same velocity. By decreasing the steering ratio, the yaw amplification increases and the steering feel is maintained.

The adaptations are mostly triggered by vehicle states, such as the vehicle speed, understeer gradient or vehicle parameters. The possibility to adapt the steering ratio based on the traffic conditions and road curvature has not yet been explored. On a straight road, less responsive steering could be preferred by the driver since little steering is needed. However, if the road gets more curvy and the vehicle speed is maintained, more steering is needed and more responsive steering could be preferred. The road curvature and the vehicle speed determine how much steering is needed for a manoeuvre, but so far only the vehicle speed is used as a trigger to adapt the steering ratio.

There have been previous studies on the usages of different steering ratios. In a study regarding the variability of the steering ratio based on the road profile, Kroes investigated the effect of a low and high steering ratio (1:12 and 1:40) on a straight and curved road [7]. On the straight road, a high steering ratio resulted in higher safety margins and a higher comfort rating compared to a low steering ratio. On the curved road, a low steering ratio resulted in higher safety margins and a higher comfort rating compared to a high steering ratio. This work showed the advantages of the usage of different steering ratios for different road profiles but since the steering ratio was passive throughout the experiment, no positive results can be guaranteed when varying the steering ratio with active steering systems.

Active systems can be classified into two groups: machine-initiated systems and driver-initiated systems. The previous cases are examples of machine-initiated systems, where the steering ratio was adapted without involvement of the driver. In this research, machine-initiated is defined as the adaptation of dynamics initiated by the machine, where the machine controls the timing of the adaptation and the driver is not responsible.

With driver-initiated systems, the driver can change the responsiveness of the steering wheel to focus more on driving comfort or on sportiness by setting the driving mode to comfort or sport/dynamic, which can be found in more luxurious cars [8] [9]. Next to the steering ratio, various other dynamical properties of active components, such as the engine or suspension, can be adapted. For example, the fuel consumption of the vehicle can be lowered to drive more economical by driving in eco mode. Here, the adaptation of the driving mode is consciously initiated by the driver, where the driver is responsible for the timing of the adaptation.

Active steering systems directly influence the steering input of the driver. Strangely, the human is left out of the loop quite often when evaluating active systems. In the research of Seraslan (2014), the terms 'steering feel' and 'driver comfort' were used as metrics to describe the performance of the steering system, even though the effect on driving behavior and driver acceptance was disregarded [6]. Active vehicle dynamics are commonly assessed on driver comfort and handling performance without considering subjective measures to validate the objective measures from simulations or field tests [10]. In general, only objective evaluation criteria, determined with measures such as longitudinal, lateral or vertical accelerations and rotations of the vehicle chassis, are used to evaluate active vehicle dynamics. Even if the steering behavior of the driver is considered, a reduced steering wheel angle and velocity is mainly used to determine the driver's physical workload has been reduced, instead of validating the objective steering data with subjective measures from questionnaires [11] [12].

The effects of machine-initiated and driver-initiated systems have already been investigated in automation studies and these studies show interesting insights. According to Miller and Parasuraman (2007), there is a trade-off between human workload and unpredictability in machine-initiated and driver-initiated systems [13]. As described by Kidwell et al. (2012), machine-initiated systems tend to reduce the human workload by decreasing the user involvement as a result of decreased responsibility in system control, but are also more unpredictable. On the other hand, driver-initiated systems tend to increase the cognitive demand since there is an increase in the user's responsibility for system supervision, with the benefit that the adaptations are more predictable to the driver [14].

The trade-off between human workload and unpredictability needs to be taken into account when designing machine-initiated and driver-initiated systems. Especially the unpredictability of machine-initiated systems can be an issue when the steering response is altered during driving. This is the main reason why the active steering system in the BMW 5 Series was poorly reviewed [15]. The steering feel was described as "artificial" and "distant" since the adaptation of the steering ratio was unpredictable. In adaptive automation studies, these problems have also been addressed. According to Kaber et al. (2001), effective communication between complex system components is crucial for overall system success [16]. A solution was suggested by Woods, Roth, and Bennett (1990), i.e. presenting the machine's current state, goals, knowledge, hypothesis and intentions to the human [17]. This solution could be useful for the problems which machine-initiated steering designs are facing, such as unpredictable adaptation behavior. However, this solution has yet to be implemented in current machine-initiated steering systems. This shows that investigating the effects on driving behavior and driver acceptance is a crucial step in the development of machine-initiated systems.

The aim of this research was to examine the effects of machine-initiated and driver-initiated steering systems on driving behavior and driver acceptance. It was hypothesized that drivers would have a preferred steering response for each section, i.e. a steering response between slow and fast during overtaking of traffic vehicles, a slow steering response on the straight road, and a fast steering response on the curved road. Furthermore, it was hypothesized that the active steering systems would reduce the objective and perceived driver effort compared to passive steering systems. Finally, it was hypothesized that between machine-initiated and driver-initiated steering there would be a trade-off between effort and acceptance, i.e. a higher acceptance for driver-initiated steering but also a higher mental effort compared to machine-initiated steering.

II. Methods

A. Participants

Twenty-four participants (20 male, 4 female) between 22 and 30 years old (M = 24.9, SD = 2.0) with a valid driving license and normal or corrected-to-normal vision participated in this study. Prior to the experiment, a driving experience questionnaire was filled out by the participants. Here, thirteen participants answered that human powered transportation (e.g. walking, cycling) was their primary mode of transportation, six automobile, four public transportation and one motorcycle. On average, one participant drove less than once a month, eight drove less than once a week, thirteen drove 1-3 days a week and two drove 4-6 days a week. Regarding mileage in the past 12 months, six participants drove 1-1000 km, eight 1000-5000 km, seven 5000-10000 km, two 10000-15000 km and one participant drove 15000-20000 km. The participants were also asked about their experience regarding the usage of driving modes in cars since it gives an interesting insight in the driver's willingness to switch between modes, and it could also have an effect on the adaptation behavior of the driver during the experiment. Here, seven participants answered to have never driven in a car with different driving modes, five answered to have driven in a car with different modes without using them, seven answered to rarely use different driving modes, four answered to use different driving modes sometimes and one participant answered to use different driving modes most of the time.

B. Apparatus

The experiment was conducted in a fixed-base driving simulator at the Cognitive Robotics lab at the Faculty of Mechanical Engineering (3mE), Delft University of Technology. The simulation was developed using JOAN (Beckers et al., 2021), an open-source software framework developed at Delft University of Technology, which builds on the CARLA open-source simulator (Version 0.9.8; Dosovitskiy et al., 2017) [18] [19]. The SensoDrive steering system was used to provide self-aligning torques on the steered front-wheels. The spring stiffness of the steering wheel was set at 2.20 Nm/rad and the damping ratio was set at 0.60 $Nm \cdot s/rad$. The steering wheel angle and steering wheel velocity from the SensoDrive were filtered with a zero-phase 2nd order Butterworth filter for the data analysis. Since the vehicle had a constant velocity, there were no gas and brake pedals. A 65 inch 4K screen was used to show the vehicle environment (figure 1) with a frame rate of 60 Hz. An Audi S4 with an automatic gearbox was used to simulate the vehicle dynamics. The steering wheel was visible during the experiment to give the driver the visual confirmation when applying an angle on the steering wheel. The datarecorder recorded at 100 Hz, whereas the update-rate of the vehicle environment was 80 Hz on average. For the driver-initiated steering system, a mouse was attached to the back of the steering wheel within comfortable reach when holding the steering wheel at a ten-to-two position (left bottom corner figure 1).

Fig. 1. The hardware setup and virtual simulator environment during the experiment. The blue dashboard display shows the communication to the driver about the steering response in use. Left bottom corner shows the attached mouse for driver-initiated steering.

C. Machine-initiated and driver-initiated design

Two steering responses were used during the experiment with the following specifications:

- Slow steering response: steering ratio of the front-wheels of 1:25.
- Fast steering response: steering ratio of the front-wheels of 1:12.5. The slow and fast steering response differ by a factor of two.

The steering response in use was visually communicated to the driver through a small dashboard display which was either blue for the slow steering response (figure 1) or red for the fast steering response. With machine-initiated and driver-initiated steering, the steering response was adapted during driving. The transition between steering responses was not instantaneous but gradually. The angle exerted on the steering wheel was multiplied by a gain K_δ, which altered the steering wheel angle in the virtual environment. The gain had a value of one for the slow steering response and a value of two for the fast steering response. For an adaptation between steering responses, the gain at the next time step K_{i+1} was calculated with equation 1. The hardware was running at 100 Hz, which means the transition between steering responses took approximately 3.5 seconds. The adaptation was communicated to the driver by changing the color of the dashboard display with a gradient between blue and red.

$$K_{\delta,i+1} = \begin{cases} K_{\delta,i} * 1.002 & \text{if } K_i < 2 \text{ (Slow} \rightarrow \text{Fast)} \\ K_{\delta,i}/1.002 & \text{if } K_i > 1 \text{ (Fast} \rightarrow \text{Slow)} \end{cases} \quad (1)$$

The adaptations with machine-initiated steering occurred on predefined locations and the adaptation logic was based on the traffic and road conditions:

- Traffic: if the distance between the traffic vehicles dropped below the limit of 60 meters, the machine adapted from the slow to the fast steering response. If

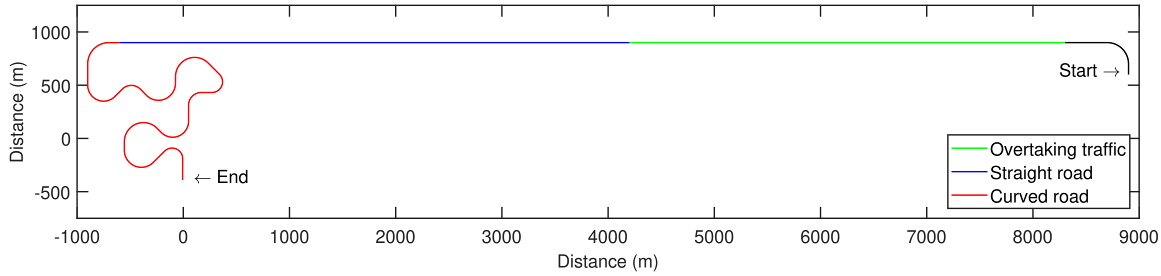

Fig. 2. A top view of the test track.

the distance between the traffic vehicles exceeded the limit of 60 meters, the machine adapted from the fast to the slow steering response. In the experiment, during the overtaking section, the machine switched once to the fast steering response and once to the slow steering response (fig 6, top figure).

- Road curvature: on the straight road, the machine switched to the slow steering response, and 100 meters before the curved road, the machine switched to the fast steering response (fig 6, top figure).

The driver-initiated steering system allowed the driver to switch between the slow and fast steering response by clicking the left and right mouse button. The default steering response of the steering system was the slow steering response. If the right mouse button was pressed, the steering system switched to the fast steering response, and if the left mouse button was pressed, the steering system switched to the slow steering response. Again, the adaptation was communicated to the driver by changing the color of the dashboard display. During the experiment, an advice by the steering system was given about the suggested steering response. This advice was based on the adaptation logic for machine-initiated steering and was shown as a red arrow next to the speed indicator. If the fast steering response was driven by the driver and the machine would drive with the slow steering response, a red arrow down was shown, and if the slow steering response was driven by the driver and the machine would drive with the fast steering response, a red arrow up was shown. If the driver used the same steering response as the machine would, no indicator was shown.

D. Road environment

The test track was a one-way two-lane highway consisting of three sections: overtaking traffic vehicles, driving on a straight road and driving on a curved road, as shown in figure 2. In the first section, the driver was instructed to overtake traffic vehicles on a straight road. The driver was driving with a fixed velocity of 100 km/h and the traffic vehicles had a fixed velocity of 60 km/h. The distance between the traffic vehicles was predetermined and constant during the experiment but could vary 0.5 meters between trials due to software shortcomings. In the experiment, the vehicle density of the traffic vehicles varied by first increasing and then decreasing, as can be seen in figure 4 (top figure). The traffic vehicles drove on the left and right lane (figure 3) and had a fixed straight trajectory, therefore the driver was instructed to overtake the traffic vehicles on both lanes of the road in a slalom manoeuvre. The second section was on a straight road without traffic vehicles and the driver was instructed to follow the right lane. The third and final section consisted of a curved road with varying road curvature and without traffic vehicles, as can be seen in figure 4. Also here, the driver was instructed to follow the right lane. The results were analysed per section and the sections were defined as follows:

1) Overtaking traffic: from the overtake of the first traffic vehicle (x = 715 m) up to the last overtake (x = 4815 m), total distance 4200 meters.
2) Straight road: from the last overtake (x = 4815 m) up to 100 meters before the first turn (x = 9615 m), total distance 4800 meters.
3) Curved road: 100 meters before the first turn (x = 9615 m) up to 40 meters after the last turn (x = 14355 m), total distance 4740 meters.

Fig. 3. An example of the alternately positioned traffic vehicles on both lanes of the road during the overtaking section of the experiment.

E. Experimental design

The participant was instructed to drive as he or she normally would and complete the track safely. Prior to the real experiment, the participant drove on a test track consisting of straight and curved roads with the slow and fast steering response to become familiar with the steering system and the virtual simulator environment. Prior to each condition, the participant drove once on a test track with the settings of the condition. Here, the participant could become familiar with the adaptation of the steering response. The conditions were fully counterbalanced and had the following specifications:

1) Passive Slow (PS): fixed slow steering response.
2) Passive Fast (PS): fixed fast steering response.
3) Machine-initiated (MI): the adaptation between steering responses was machine-initiated and followed the logic explained in section C.
4) Driver-initiated (DI): the adaptation between steering responses was driver-initiated, the default steering response was slow.

After each condition, the participant was asked to fill out the NASA-TLX workload questionnaire and an additional questionnaire about the effort it took to complete each section (Appendix D.2). After the experiment, the participant was asked to fill out a post-experiment questionnaire (Appendix D.3).

F. Dependent measures

The data analysis was divided into three parts. First, the situational benefits and limitations were investigated for the passive slow and passive fast steering system both objectively and subjectively. This was done to understand what the benefits and limitations of the slow and fast steering response were in terms of effort and acceptance for each section, i.e. overtaking traffic vehicles, driving on a straight road and driving on a curved road. Next, the situational benefits and limitations were investigated for the machine-initiated (MI) and driver-initiated (DI) steering system compared to each other and the passive steering systems. The adaptations between the slow and fast steering response with the MI and DI steering system were also mapped to find out where the adaptations with DI occurred compared to MI. Finally, the transition period after an adaptation between steering responses for both MI and DI steering was analysed to see if the adaptations affected the steering behavior and how this affected the effort and acceptance. The following measures were used:

- *RMS steering wheel angle* was used as an objective measure of physical workload. The spring stiffness of the steering wheel was linear, which means the angles exerted on the steering wheel were proportional to the torques. As such, the RMS steering wheel angle can be seen as a measure of physical workload.
- *RMS front-wheel angle* was used as a second measure of workload. The RMS front-wheel angle was taken as a dependent measure since this is the output of the steering wheel angle with conversion of the steering ratio.
- *RMS steering wheel velocity* is used as an objective measure of steering wheel steadiness.
- *Maximum absolute lateral deviation* was used as an objective measure of lane-following accuracy. The lateral deviation was measured from the center of the right-lane on the straight and curved road.
- *Subjective effort* was used as measure to quantify the perceived effort of the driver per section. It was determined by means of a questionnaire. After each trial, the participant was asked to answer the question "it took me little effort to complete this section" on a seven-point scale from 'agree' (1) to 'disagree' (7) for each of the three sections i.e. overtaking traffic vehicles, driving on a straight road and driving on a curved road.
- *NASA-TLX* was used to determine the workload of the participant on six aspects: mental demand, physical demand, temporal demand, performance, effort and frustration. Items were scored on a 21-point scale and the overall score was the mean of the six subscores (Hart and Staveland, 1988) [20].
- *Steering response preference* was used as a subjective measure for acceptance of the steering response. By means of a post-questionnaire, the participant was asked which steering response was preferred for each section on a seven-point scale.
- *Steering system ranking* was used as a subjective measure for system acceptance and was determined by means of a questionnaire. In the post-experiment questionnaire, the participant was asked "rank the four conditions from 1 (most preferred) to 4 (least preferred), you can only use each number once".

G. Statistical Analysis

For each dependent measure, a 24 $\times$ 4 matrix was obtained (24 participants, 4 conditions). The mean (M), standard deviation (SD) and the corrected within-subject normalised confidence interval (CI) was calculated for each dependent measure and condition, where the corrected within-subject normalised CI was calculated as described by Morey et al. (2008) [21]. Furthermore, the 24 $\times$ 4 matrix was rank-transformed according to Conover and Iman (1981) to account for possible violations of the assumption of normality associated with parametric tests [22]. The rank-transformed matrix was submitted to a repeated measures ANOVA with the four conditions (PS, PF, MI and DI) as within-subjects factor. To account for the possibility of false positive significance, Bonferroni corrections were applied to the six pairwise comparisons between the conditions (Weisstein, 2004) [23]. The effect sizes for pairwise comparisons d_z were calculated using equation 2, where μ_{x-y} is the mean of the difference and σ_{x-y} is the standard deviation of the difference (Faul et al., 2007) [24]. Furthermore, associations between dependent measures were assessed by means of Spearman rank-order correlation coefficients (Appendix A).

$$d_z = \frac{|\mu_{x-y}|}{\sigma_{x-y}} \quad (2)$$

TABLE I

MEANS (M), STANDARD DEVIATION (SD), EFFECT SIZES (d_z), RESULTS OF THE REPEATED MEASURES ANOVA (p, F) AND PAIRWISE COMPARISON FOR DEPENDENT MEASURES, GROUPED PER SECTION. X: $p < 0.05$, XX: $p < 0.01$, XXX: $p < 0.001$

		Conditions					Pairwise Comparisons					
		PS (1)	PF (2)	MI (3)	DI (4)		1–2	1–3	1–4	2–3	2–4	3–4
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	p value $F(3, 69)$	p (d_z)	p (d_z)	p (d_z)	p (d_z)	p (d_z)	p (d_z)
Overtaking traffic	Subjective effort (-)	2.54 (1.50)	1.96 (1.00)	2.25 (1.48)	1.83 (1.24)	$p = 0.037$ $F = 3.00$	(0.39)	(0.21)	(0.58)	(0.12)	(0.29)	(0.33)
	RMS steering wheel angle (deg)	6.32 (1.39)	3.38 (0.96)	4.05 (1.08)	3.99 (1.06)	$p = 1.51 \times 10^{-21}$ $F = 74.17$	xxx (3.17)	xxx (2.42)	xxx (2.13)	xx (0.91)	x (0.69)	(0.02)
	RMS Front-wheel angle (deg *10)	2.53 (0.56)	2.71 (0.77)	2.79 (0.82)	2.58 (0.63)	$p = 0.22$ $F = 1.51$	(0.23)	(0.46)	(0.10)	(0.15)	(0.13)	(0.34)
	RMS steering wheel velocity (deg/s)	11.11 (4.33)	7.34 (3.30)	8.28 (3.82)	7.95 (3.08)	$p = 6.93 \times 10^{-8}$ $F = 15.70$	xxx (1.14)	xxx (1.09)	xxx (1.27)	(0.34)	(0.27)	(0.04)
Straight road	Subjective effort (-)	1.42 (0.78)	2.21 (1.50)	1.46 (0.66)	1.63 (0.92)	$p = 0.005$ $F = 4.63$	x (0.65)	(0.17)	(0.41)	(0.48)	(0.34)	(0.22)
	RMS steering wheel angle (deg)	0.85 (0.43)	0.59 (0.29)	0.79 (0.36)	0.69 (0.25)	$p = 4.13 \times 10^{-6}$ $F = 11.28$	xxx (0.95)	(0.23)	x (0.62)	xx (0.85)	(0.51)	(0.39)
	RMS Front-wheel angle (deg *10)	0.34 (0.17)	0.47 (0.23)	0.31 (0.15)	0.31 (0.11)	$p = 1.84 \times 10^{-6}$ $F = 12.12$	xx (0.76)	(0.29)	(0.18)	xxx (1.14)	xx (0.81)	(0.11)
	RMS steering wheel velocity (deg/s)	2.57 (1.10)	2.06 (1.00)	2.37 (1.26)	2.31 (0.90)	$p = 0.003$ $F = 5.05$	x (0.67)	(0.45)	(0.37)	(0.42)	(0.37)	(0.05)
	Maximum absolute lateral deviation (m)	0.74 (0.21)	0.76 (0.26)	0.76 (027)	0.73 (0.22)	$p = 0.98$ $F = 0.05$	(0.07)	(0.05)	(0.08)	(0.02)	(0.01)	(0.03)
Curved road	Subjective effort (-)	3.75 (1.48)	2.71 (1.23)	2.29 (0.81)	2.92 (1.28)	$p = 8.10 \times 10^{-6}$ $F = 10.60$	x (0.70)	xxx (1.12)	x (0.67)	(0.36)	(0.16)	(0.57)
	RMS steering wheel angle (deg)	31.53 (0.49)	15.74 (0.25)	15.72 (0.19)	16.87 (3.26)	$p = 5.36 \times 10^{-23}$ $F = 84.08$	xxx (3.42)	xxx (3.81)	xxx (1.98)	(0.05)	x (0.69)	xx (0.73)
	RMS Front-wheel angle (deg *10)	12.61 (0.20)	12.60 (0.20)	12.58 (0.15)	12.61 (0.19)	$p = 0.64$ $F = 0.56$	(0.16)	(0.13)	(0.09)	(0.03)	(0.23)	(0.24)
	RMS steering wheel velocity (deg/s)	20.37 (4.38)	12.11 (2.62)	13.47 (9.48)	15.25 (14.21)	$p = 4.42 \times 10^{-21}$ $F = 71.18$	xxx (2.59)	xxx (2.81)	xxx (2.19)	(0.09)	(0.23)	(0.29)
	Maximum absolute lateral deviation (m)	1.99 (0.65)	1.65 (0.56)	1.65 (0.64)	1.95 (0.79)	$p = 7.56 \times 10^{-4}$ $F = 6.31$	x (0.63)	xx (0.77)	(0.36)	(0.12)	(0.33)	x (0.58)
Overall	NASA-TLX Overall (%)	33.13 (15.87)	31.81 (13.52)	28.75 (10.70)	31.01 (12.71)	$p = 0.28$ $F = 1.31$	(0.05)	(0.31)	(0.20)	(0.25)	(0.10)	(0.25)
	System acceptance (-)	3.25 (0.90)	2.79 (0.93)	2.13 (1.26)	1.83 (0.82)	$p = 1.99 \times 10^{-4}$ $F = 7.53$	(0.32)	x (0.62)	xxx (1.05)	(0.34)	xx (0.78)	(0.16)

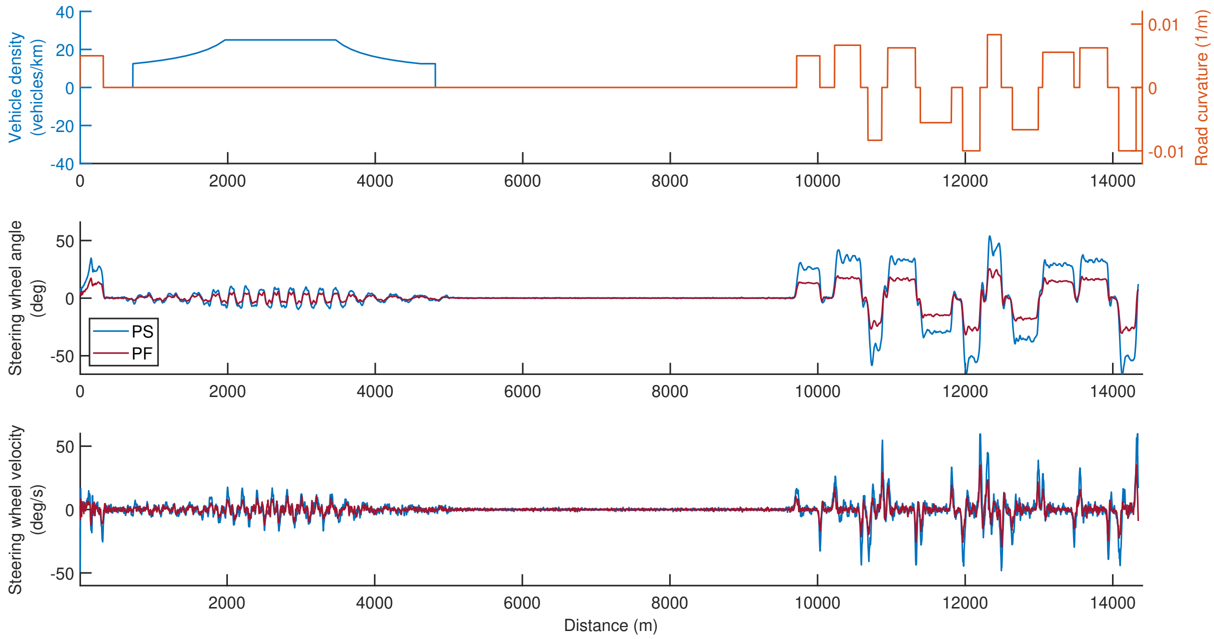

Fig. 4. Vehicle density and road curvature (top), mean steering wheel angle (middle) and mean steering wheel velocity (bottom) over twenty-four participants for the passive steering systems plotted against the distance.

III. Results

A. Analysis of passive steering systems

In figure 4 the mean steering wheel angle and mean steering wheel velocity are shown for the passive steering systems. During overtaking and on the curved road, the steering wheel angles with the slow steering response were larger compared to the steering angles with the fast steering response. This was also the case on the straight road, though the magnitude of the steering wheel angle was much smaller, as shown in table I. Furthermore, the magnitude of the vehicle density and road curvature corresponds with the magnitude of the steering wheel angle. The peaks of the steering wheel velocity were also higher with the slow steering response compared to the peaks with the fast steering response.

Table I shows the means, standard deviations, effect sizes and results of the repeated measures ANOVA for the dependent measures. In all sections, the RMS steering wheel angle and velocity were lower with the fast steering response than with the slow steering response, which can also be seen in figure 4. The pairwise comparison between PS and PF of the RMS steering wheel angle shows that the p value is smaller than 0.001 for each section. The RMS front-wheel angle shows different results. During overtaking and on the curved road, there was no significant difference in the RMS front-wheel angle between the slow and fast steering response. On the straight road, the RMS front-wheel angle with the slow steering response was significantly lower compared to the RMS front-wheel angle with the fast steering response.

The maximum absolute lateral deviation shows no significant difference between the slow and fast steering response on the straight road. On the curved road, the maximum absolute lateral deviation was significantly higher with the slow steering response compared to the deviation with the fast steering response.

In the sections which demanded more steering action i.e. overtaking traffic and driving on a curved road, the subjective effort was significantly higher with the slow steering response compared to the fast steering response. On the straight road, where little steering action was required, the fast steering response led to a higher subjective effort compared to the slow steering response. The means of the subjective effort were significantly different between PS and PF for each section (overtaking: $p = 0.037$, $F = 3.00$, straight road: $p = 0.005$, $F = 4.63$, curved road: $p = 8.10 \times 10^{-6}$, $F = 10.60$).

Figure 5 shows the answers of the questionnaire regarding the preferred steering response for each section on a seven-point scale. During overtaking, a steering response between slow and fast was preferred, on the straight road a slow steering response was preferred, and on the curved road a fast steering response was preferred.

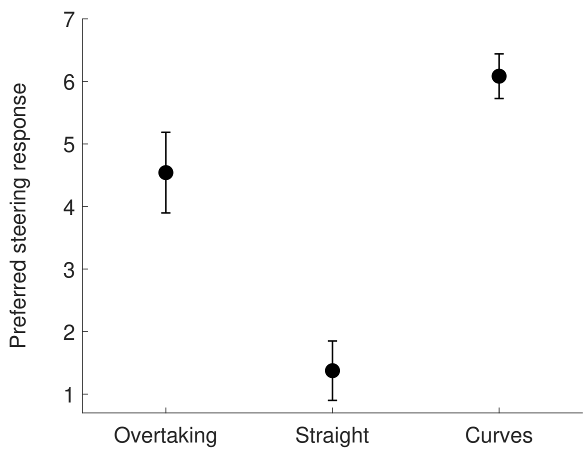

Fig. 5. Subjective preferred steering response for each section rated between one (slow steering response) and seven (fast steering response). Means and within-subject 95% CI are shown.

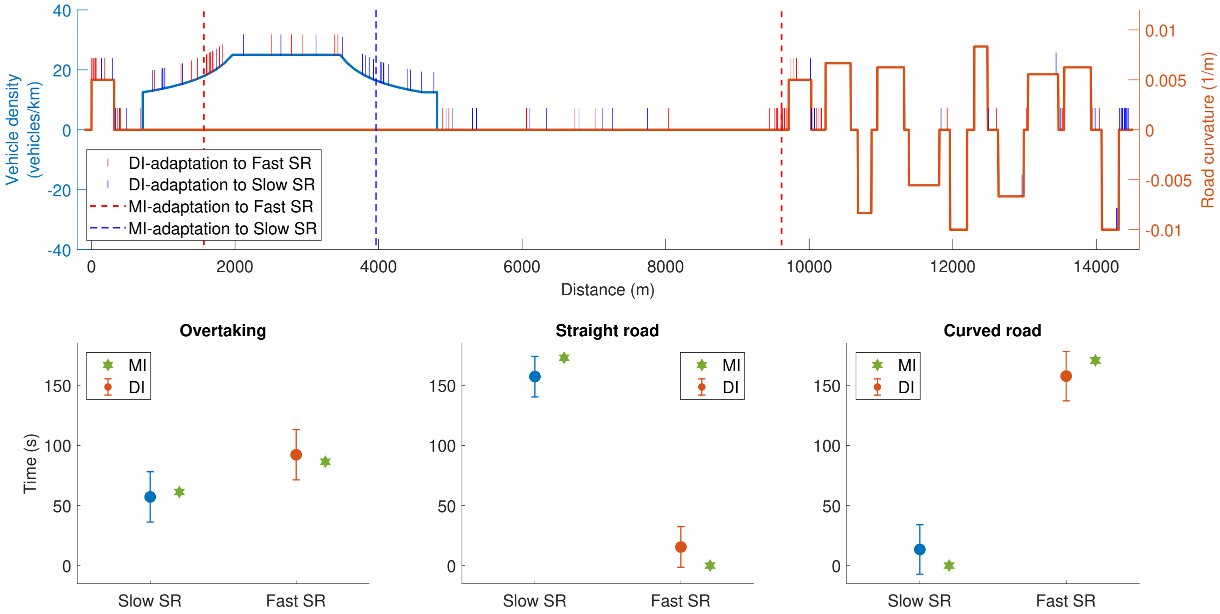

Fig. 6. Adaptations between steering responses plotted against the vehicle density and road curvature (top figure) and total time driven with the slow and fast steering response (bottom figures) for each section during machine-initiated (MI) and driver-initiated (DI) steering.

B. Analysis of active steering systems

The machine switched on three predetermined locations between steering responses i.e. twice during overtaking of traffic vehicles and once 100 meters before the curved road. The machine-initiated adaptations were initiated at the same positions for all participants. Together with the driver-initiated adaptations, this is shown in figure 6 (top figure), where the number of adaptations per section is shown in table II. In the bottom figures, the total time driven with the slow and fast steering response is shown for the machine-initiated (MI) and driver-initiated (DI) condition. The total time driven with each steering response for the DI condition shows that during overtaking both the slow and fast steering response were used, on the straight road the slow steering response was mainly used and on the curved road the fast steering response was mainly used. No significant difference was found between MI and DI for the time driven with each steering response for each section.

The driver-initiated adaptations in figure 6 show that as the vehicle density increased, most of the participants adapted to the fast steering response and as the vehicle density decreased, the participants preferred the slow steering response. At the maximum vehicle density only six participants adapted the steering response. After the last overtake manoeuvre, fifteen participants adapted the steering response at least once on the straight road. Before the first or second turn, most of the participants switched to the fast steering response. Only seven participants switched in between turns. One participant drove the entire curved road with the slow steering response whereas sixteen participants drove only with the fast steering response. After the last turn, most participants switched back to the slow steering response.

Table I shows that there was no significant difference in subjective effort between MI and DI for each section. The perceived effort on the curved road with MI and DI was significantly lower than with PS. The RMS steering wheel angle and velocity show that only on the curved road there was a difference between MI and DI i.e. the RMS steering wheel angle was higher with DI compared to MI.

TABLE II
PARTICIPANTS WITH AT LEAST ONE ADAPTATION, NUMBER OF DRIVER-INITIATED ADAPTATIONS TO THE SLOW AND FAST STEERING RESPONSE AND TOTAL WITH STANDARD DEVIATION (SD), PER SECTION

	# Participants	# Driver-initiated adaptations			
		Slow to Fast	Fast to Slow	Total	*SD*
Pre-overtaking	15	15	5	20	0.87
Overtaking	23	21	27	48	1.06
Straight road	15	14	10	24	1.18
Curved road	18	23	25	48	1.72

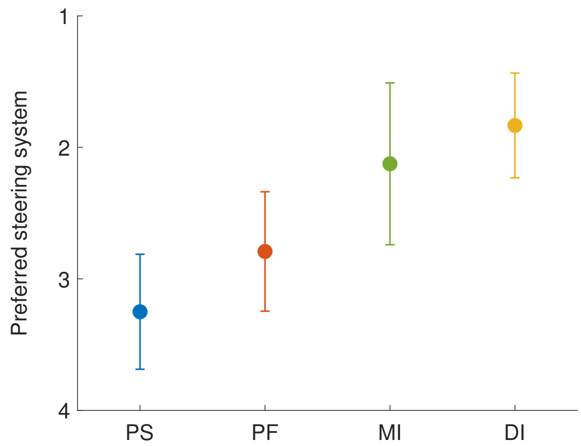

Fig. 7. Subjective preferred steering system, where one is the most preferred steering system and four is the least preferred steering system. Means and within-subject 95% CI are shown.

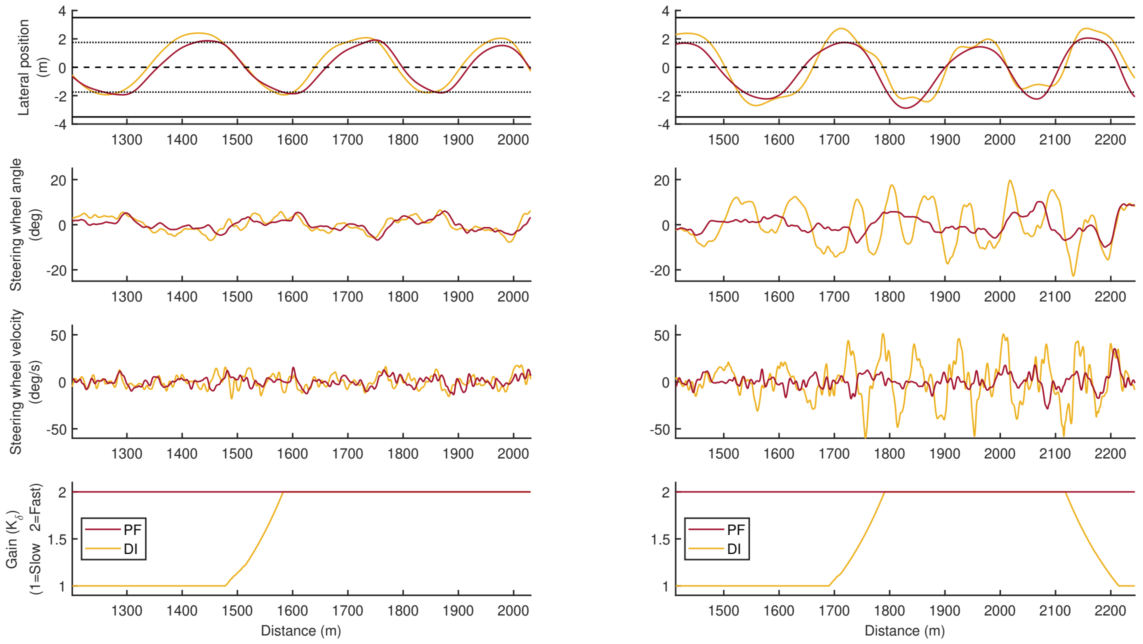

Fig. 8. The lateral position, steering wheel angle, steering wheel velocity and steering mode for P12 (left figures) and P17 (right figures) during the 10 seconds before and the 20 seconds after an adaptation to the fast steering response during overtaking with the PF and DI condition.

Figure 7 shows the subjective preferred steering system. As shown in table I, the mean scores between the conditions differ significantly. Both active steering systems (MI and DI) scored significantly better than PS. Furthermore, DI scored significantly better than PF. Noticeable is that thirteen participants preferred at least one of the passive steering systems over one of the active steering systems. The questionnaire showed that thirteen participants preferred to switch between steering responses themselves (DI) and eleven participants preferred to let the machine change the steering response (MI).

C. Transition period between steering responses

Figure 8 shows the steering behavior after an adaptation from the slow to the fast steering response of two exemplary participants (P12 and P17) during overtaking in the PF and DI condition. The left figures show the steering behavior of a smooth transition and the right figures show the steering behavior of an unstable transition. The PF condition is chosen as a baseline since the steering response after the adaptation was the same in both conditions.

The left figures of the smooth transition show that there was no substantial change in steering wheel angle and velocity after the driver-initiated adaptation. For both PF and DI, the steering behavior was consistent during overtaking of the traffic vehicles. The right figures of the unstable transition show that after the adaptation, there was an increase in steering wheel angle and steering wheel velocity. The increase in steering action resulted in a lateral position which was less smooth than with PF. The driver swerved more from left to right on the road. After approximately fifteen seconds, the participant adapted back to the slow steering response, which is visible in the steering gain (bottom figure). With PF, the participant overtook the traffic vehicles with consistent steering behavior.

To find out if the machine-initiated and driver-initiated adaptations led to an increased steering output, the RMS front-wheel angle was analysed for the ten seconds after an adaptation between steering responses. Figure 9 shows the RMS front-wheel angle during three periods i.e. the overtaking section, the first ten seconds after an adaptation to the fast steering response and the first ten seconds after an adaptation to the slow steering response for the four conditions. In the MI condition, the twenty-four adaptations to the slow and fast steering response were initiated at the same position. Since there were no adaptations in the passive conditions (PS and PF), the same ten seconds as during the MI condition were taken as a reference. For the DI condition, all adaptations during overtaking were taken into account (21 adaptations to the fast SR, 27 adaptations to the slow SR), where 23 participants switched at least once. Here, the assumption is made that the adaptations in the active conditions (MI and DI) occurred roughly at the same moment to be able to compare the four conditions.

The RMS front-wheel angle during the overtaking section shows no significant difference between the four conditions, which is also visible in table I. However, in the ten seconds after an adaptation to the fast steering response, the RMS front-wheel angle with driver-initiated steering was significantly higher than both passive steering systems (PS and PF). This was not the case for the ten seconds after a machine-initiated adaptation to the fast steering response. It is also noticeable that the spread was larger with driver-initiated steering than with machine-initiated steering. In the ten seconds after an adaptation to the slow steering response, there was no significant difference between the RMS front-wheel angle of the four conditions, although it was slightly higher with driver-initiated steering.

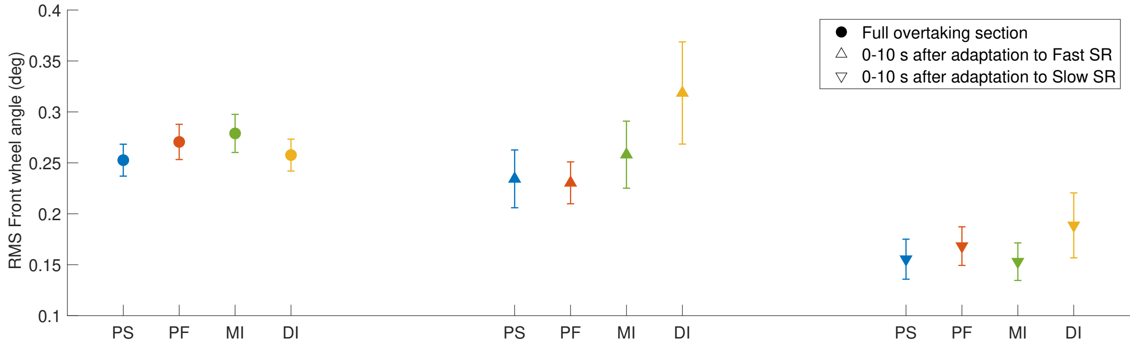

Fig. 9. The RMS front-wheel angle for the four conditions for three periods: the overtaking section, ten seconds after an adaptation to the fast steering response and ten seconds after an adaptation to the slow steering response. Means and within-subject 95% CI are shown.

IV. Discussion

A. Main results

The aim of this research was to investigate the effects of machine- and driver-initiated steering systems on driving behavior and driver acceptance. The situational benefits and limitations of the slow and fast steering response were analysed both subjectively and objectively. As expected, the participants indicated that for the three sections (i.e. overtaking, straight road and curved road) different steering responses were preferred i.e. a steering response between slow and fast during overtaking, a slow steering response on the straight road, and a fast steering response on the curved road. This corresponds with the research done by Kroes (2019), who found that a slow steering response was preferred on a highway road and a fast steering response on a country road [7]. More importantly, this is an indication that an active steering system could be useful for these situations.

Next, this research showed that participants were also willing to adapt the steering response which indicates that the driver-initiated steering system was useful. The majority of the adaptations by the driver occurred around the same location as the predetermined machine-initiated adaptations. This shows that the machine-initiated steering systems was well designed since it matched with the adaptation behavior of the driver. This is also shown by the fact that the total time driven with the slow and fast steering response in the MI and DI condition were equal for each section. Furthermore, the best rated steering systems were machine- and driver-initiated steering and they were preferred over the passive steering systems. The steering response which resulted in the lowest effort was chosen for each section with machine- and driver-initiated steering, which directly shows the advantage of the active steering systems. Between MI and DI, there were no significant differences, though an adaptation resulted in an unstable transition in some cases.

B. Evaluation of preferred steering response

For each section, the preferred steering response corresponded with the steering response which resulted in the lowest perceived effort i.e. a steering response between slow and fast during overtaking, a slow steering response on the straight road, and a fast steering response on the curved road. The preferred steering response could also be explained by the objective steering results. During overtaking, the steering input (i.e. the steering wheel angle and steering wheel velocity), showed significantly higher values with PS than PF. Since the steering wheel angle is proportional to the steering torque and thus the physical workload, the preference for a faster steering response can be explained. On the straight road, the subjective effort was significantly higher with PF than with PS. However, the RMS steering wheel angle and steering wheel velocity did not show higher values with PF than with PS. The preference for a slow steering response can be explained by looking at the RMS front-wheel angle, which showed significantly higher values with PF than PS. Since only little steering action was needed to follow the straight road, the increase in RMS front-wheel angle with PF compared to PS is an explanation for the increase in subjective effort and also the preference for the slow steering response. On the curved road, the RMS steering wheel angle and steering wheel velocity were significantly higher with PS than PF. The steering wheel angle was close to a factor of two higher with PS than with PF, which is the ratio between the slow and fast steering response. Since the physical workload was significantly higher with PS than PF, the fast steering response was preferred by the drivers.

These results have shown that neither the RMS steering wheel angle nor the RMS front-wheel angle are decisive when finding an explanation for the preferred steering response through objective data. The choice was made to not use the steering wheel reversal rate (SRR) or steering wheel steadiness as dependent measures since these metrics are dependent on a threshold. By altering the steering wheel input, these metrics could lead to unreliable and unexpected results (Kroes (2019), SRR) [7]. However, even by taking the RMS steering wheel angle and velocity as dependent measures, the results were odd. The RMS steering wheel angle and velocity were higher with PS than PF for each section. On the straight road, the expectation was that the steering wheel angle would be higher with PF than PS since steering with a faster steering response is more sensitive and could lead to more nervous steering, as stated by Shimizu et al. (1999) [2]. The preference for a slow steering response on the straight road could be explained by looking at the results of the front-wheel angle. With a constant velocity, a certain amount of steering was needed to overtake traffic vehicles or follow the curved road. The vehicle speed was constant at 100 km/h and the steering angle required to follow the curved road was roughly the same for all participants. However, on the straight road only little steering was needed. Even though the physical workload was higher with PS than PF, the RMS front-wheel angle was significantly lower with PS than PF. This suggests that in this case the front-wheel angle could be a measure of mental workload instead of physical workload. On the straight road, drivers could prefer a lower mental workload over a lower physical workload.

C. Evaluation of active steering systems

The active steering systems were better rated than the passive steering systems (figure 7). The mean score on the question "were the adaptations by the machine useful for the traffic and driving situation" was 5.04 on a seven-point scale (SD = 1.71), which indicates that the adaptation itself was quite useful. The preference for machine-initiated or driver-initiated adaptation is 11 and 13 participants respectively (questionnaire), which shows that both systems have their advantages and disadvantages. After the experiment, the participants gave various reasons for preferring machine-initiated or driver-initiated steering which corresponded with results from studies on adaptive automation. According to Kidwell et al. (2012), machine-initiated steering could lead to a reduced mental effort since the machine controls the adaptation and the driver could focus on the driving task [14]. This agrees with answers from participants stating that adapting the steering response was an extra task and increased the mental effort. On the other hand, some participants felt that since the timing was unpredictable and the control was given to the machine, the mental effort increased. This trade-off between human workload and unpredictability was also mentioned by Miller and Parasuraman (2007) [13].

Next, communication plays an important role in machine- and driver-initiated steering systems. According to Kaber et al. (2001), communication is a critical factor in achieving effective human-automation integration [16]. The human operator needs to know what the machine has done, is doing, and will do next. The same principle applies to the driver-machine interaction in this experiment. The visual communication of the machine-initiated adaptation, through the dashboard display, was stated by some participants to be crucial for the sense of trust and confidence in the system. Here, it is important to recognize that the driver knew when the machine was changing the steering response through the display, but did not know about future adaptations of the machine. This could be a reason why participants preferred driver-initiated steering, since in that case the driver is always in control. Further research on the effects of communication methods of machine-initiated adaptations on driving behavior could clarify these uncertainties.

Furthermore, the advice of the steering system regarding the steering response during driver-initiated steering had an effect on the adaptations of the driver. The mean score on the question "did the advice affect your choice of steering response" was 4.33 on a seven-point scale (SD = 1.66). Whether the advice had a positive or negative effect on the driving behavior cannot be stated unambiguously, but it could explain why the adaptations with MI and DI occurred roughly around the same instance.

D. Evaluation of the transition period

As shown in figure 8, the transition between steering responses can lead to unstable steering behavior. After an adaptation, the steering input can increase for a short period of time until the driver is used to the steering response. In figure 9, the RMS front-wheel angle of the first ten seconds after an adaptation is shown, together with the RMS front-wheel angle during the entire overtaking section as a baseline. Here, the assumption was made that the machine-initiated and driver-initiated adaptations can be compared since the majority of the adaptations were around the same distance. The results show an increase in the RMS front-wheel angle after a driver-initiated adaptation to the fast steering response compared to the other three conditions. There are various key factors which could affect the steering behavior during a transition between steering responses.

First of all, the timing of the adaptation is thought to be an important design parameter. The machine-initiated adaptations were initiated at a predetermined moment when the steering action of the driver was expected to be minimal. During overtaking this was between two overtake manoeuvres, and for the curved road this was 100 meters before the first turn. This timing was chosen to prevent the machine-initiated adaptation to occur when large steering angles were applied on the steering wheel and to prevent an unwanted reaction of the driver. In this research, the timing of the machine-initiated adaptation was manually chosen. Future studies could look into more robust algorithms, based on road demand, to determine suitable adaptation moments for the machine.

Next, the transition direction has an effect on the steering behavior during a transition period. As shown in figure 9, a driver-initiated adaptation from the slow to the fast steering response during overtaking led to a higher RMS front-wheel angle compared to PS, PF and MI. This can also be seen in figure 8 (left), which shows an unstable transition from the slow to the fast steering response for a single participant. After the adaptation, the steering behavior shows a sudden increase in steering wheel angle and velocity, which did not decrease and even led to an adaptation back to the slow steering response. For the transition direction fast to slow, the RMS front-wheel angle does not increase for both machine- and driver-initiated steering. This could be explained by the fact that it is more difficult to control the vehicle precisely with the fast steering response [2]. An adaptation to the fast steering response during an intense steering task, such as overtaking traffic vehicles, could make it more difficult to adjust to for the driver. The slow steering response takes more physical effort for the driver during overtaking (table I, RMS steering wheel angle), but is less sensitive. According to Reuter and Saal (2017), a less sensitive steering response enables quieter and safer vehicle guidance [3], which could be easier to adjust to for the driver. These results indicate that the transition direction is something to take into account when designing active steering systems.

Finally, the personal driving experience determines whether the driver is comfortable with adapting the steering response and whether the transition will be steady. Furthermore, repetition could improve the transition between steering responses. The test trial did not consist of overtaking traffic vehicles, and for the drivers this could have been more challenging than expected.

E. Future work

The two steering responses were designed to each have their advantages and disadvantages for easy and demanding steering tasks. In this experiment, the choice was binary: either the slow or fast steering response was driven. For future research, it is recommended that the driver can choose from a range of steering responses to compare this with the machine-initiated design. This could clarify if the preferred steering response found in this research is accurate for the different steering tasks.

For this experiment, the traffic conditions were set against the limit of normal overtaking behavior. At the maximum vehicle density, the distance between the traffic vehicles was 40 meters. This was done intentionally to amplify the advantages and disadvantages of the slow and fast steering response. If these active steering systems were to be implemented in current vehicles, it would be essential to test these systems in realistic traffic and road environments.

Finally, the effects of free driving speed on the adaptation behavior of drivers could be investigated. Melman et al. (2017) found that haptic steering guidance enticed drivers to increase their speed, which diminished the possible safety benefits [25]. In this experiment, drivers did not have the possibility to brake before turns, as would normally be expected. Here, an adaptation to the fast steering response was preferred. Whether the adaptation behavior changes with free driving speed could be interesting to investigate.

V. Conclusion

In a driving simulator experiment, the effects of a varying steering response in machine-initiated and driver-initiated steering systems was examined by looking at the driving behavior and driver acceptance. This was evaluated for three steering tasks i.e. overtaking traffic vehicles, driving on a straight road and driving on a curved road. From the subjective and objective measures we can conclude that:

- Drivers had different steering response preferences for different road situations: we found that a steering response between slow and fast was preferred for overtaking traffic vehicles, a slow steering response for driving on a straight road and a fast steering response for driving on a curved road. This corresponded with the subjective and objective measures for effort, the steering response which led to the lowest perceived effort was preferred by the driver.
- The driver's effort over the experiment was reduced with machine-initiated and driver-initiated steering compared to the passive steering systems. Between the two active steering systems there was no significant difference.
- Drivers preferred the active steering systems (i.e. MI and DI) over the passive steering systems (i.e. PS and PF), though there was no significant difference between MI and DI.
- A transition between steering responses can lead to unstable steering behavior with both machine-initiated and driver-initiated steering.

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A
Correlation matrices

Table A.1: Spearman rank-order correlation matrix for Passive Slow condition (N=24)

	Effort, overtaking	Effort, straight	Effort, curves	RMS SWA, overtaking	RMS SWA, straight	RMS SWA, curves	RMS FWA, overtaking	RMS FWA, straight	RMS FWA, curves	RMS SWV, overtaking	RMS SWV, straight	RMS SWV, curves	Max absolute lateral error, straight	Max absolute lateral error, curves	NASA-TLX overall	Steering system ranking	Mileage
Effort, overtaking	1.00																
Effort, straight	0.37	1.00															
Effort, curves	0.75	0.47	1.00														
RMS SWA, overtaking	0.05	-0.18	0.22	1.00													
RMS SWA, straight	-0.06	-0.27	-0.31	0.43	1.00												
RMS SWA, curves	0.01	-0.07	0.13	0.39	0.49	1.00											
RMS FWA, overtaking	0.05	-0.18	0.22	1.00	0.43	0.39	1.00										
RMS FWA, straight	-0.06	-0.27	-0.31	0.43	1.00	0.49	0.43	1.00									
RMS FWA, curves	0.01	-0.07	0.13	0.39	0.49	1.00	0.39	0.49	1.00								
RMS SWV, overtaking	0.07	-0.21	0.16	0.94	0.53	0.34	0.94	0.53	0.34	1.00							
RMS SWV, straight	-0.26	-0.32	-0.41	0.29	0.88	0.28	0.29	0.88	0.28	0.43	1.00						
RMS SWV, curves	-0.17	-0.13	-0.02	0.54	0.57	0.82	0.54	0.57	0.82	0.58	0.42	1.00					
Max absolute lateral error, straight	0.17	-0.17	0.02	0.01	0.04	0.18	0.01	0.04	0.18	-0.09	-0.09	-0.06	1.00				
Max absolute lateral error, curves	0.11	-0.11	0.11	0.01	-0.03	0.38	0.01	-0.03	0.38	-0.07	-0.21	0.09	0.67	1.00			
NASA-TLX overall	0,48	0.29	0.62	0.42	-0.19	-0.03	0.42	-0.19	-0.03	0.35	-0.30	0.10	0.10	-0.12	1.00		
Steering system ranking	0.35	0.35	0.40	-0.01	-0.04	0.19	-0.01	-0.04	0.19	-0.03	0.07	-0.05	0.15	0.30	0.10	1.00	
Mileage	0.01	-0.41	0.15	-0.04	-0.18	0.17	-0.04	-0.18	0.17	-0.07	-0.22	-0.06	0.29	0.26	-0.02	-0.11	1.00
Weekly driving	-0.14	-0.01	0.13	-0.14	-0.25	-0.12	-0.14	-0.25	-0.12	-0.19	-0.10	-0.22	-0.28	-0.22	-0.10	0.03	0.47

Note: $p < 0.05$ for $|\rho| \geq 0.41$, $p < 0.01$ for $|\rho| \geq 0.52$ and $p < 0.001$ for $|\rho| \geq 0.63$

Table A.2: Spearman rank-order correlation matrix for Passive Fast condition (N=24)

	Effort, overtaking	Effort, straight	Effort, curves	RMS SWA, overtaking	RMS SWA, straight	RMS SWA, curves	RMS FWA, overtaking	RMS FWA, straight	RMS FWA, curves	RMS SWV, overtaking	RMS SWV, straight	RMS SWV, curves	Max absolute lateral error, straight	Max absolute lateral error, curves	NASA-TLX overall	Steering system ranking	Mileage
Effort, overtaking	1.00																
Effort, straight	0.25	1.00															
Effort, curves	0.66	0.40	1.00														
RMS SWA, overtaking	-0.01	0.04	0.05	1.00													
RMS SWA, straight	-0.23	0.00	-0.36	0.47	1.00												
RMS SWA, curves	-0.19	0.07	-0.07	0.37	0.51	1.00											
RMS FWA, overtaking	-0.01	0.04	0.05	1.00	0.47	0.37	1.00										
RMS FWA, straight	-0.23	0.00	-0.36	0.47	1.00	0.51	0.47	1.00									
RMS FWA, curves	-0.19	0.07	-0.07	0.37	0.51	1.00	0.37	0.51	1.00								
RMS SWV, overtaking	0.07	-0.09	0.05	0.92	0.51	0.41	0.92	0.51	0.41	1.00							
RMS SWV, straight	-0.35	-0.07	-0.50	0.41	0.93	0.56	0.41	0.93	0.56	0.43	1.00						
RMS SWV, curves	-0.03	0.13	-0.12	0.37	0.56	0.78	0.37	0.56	0.78	0.50	0.56	1.00					
Max absolute lateral error, straight	0.07	-0.13	-0.21	0.15	0.53	0.21	0.15	0.53	0.21	0.18	0.57	0.27	1.00				
Max absolute lateral error, curves	0.20	0.22	0.08	-0.06	0.23	0.25	-0.06	0.23	0.25	-0.12	0.20	0.19	0.47	1.00			
NASA-TLX overall	0.26	0.43	0.52	0.43	0.13	-0.02	0.43	0.13	-0.02	0.29	0.00	-0.01	-0.12	-0.04	1.00		
Steering system ranking	0.35	0.27	0.36	0.00	-0.18	0.04	0.00	-0.18	0.04	0.03	-0.21	-0.03	-0.37	-0.18	0.46	1.00	
Mileage	-0.04	0.26	-0.05	-0.33	-0.12	0.28	-0.33	-0.12	0.28	-0.39	-0.06	0.10	0.10	0.31	-0.06	0.09	1.00
Weekly driving	0.02	0.28	-0.15	-0.19	-0.06	-0.09	-0.19	-0.06	-0.09	-0.24	-0.01	-0.06	-0.05	-0.23	-0.06	0.05	0.47

Note: $p < 0.05$ for $|\rho| \geq 0.41$, $p < 0.01$ for $|\rho| \geq 0.52$ and $p < 0.001$ for $|\rho| \geq 0.63$

Table A.3: Spearman rank-order correlation matrix for Machine Initiated condition (N=24)

	Effort, overtaking	Effort, straight	Effort, curves	RMS SWA, overtaking	RMS SWA, straight	RMS SWA, curves	RMS FWA, overtaking	RMS FWA, straight	RMS FWA, curves	RMS SWV, overtaking	RMS SWV, straight	RMS SWV, curves	Max absolute lateral error, straight	Max absolute lateral error, curves	NASA-TLX overall	Steering system ranking	Mileage
Effort, overtaking	1.00																
Effort, straight	0.40	1.00															
Effort, curves	0.06	0.31	1.00														
RMS SWA, overtaking	0.18	-0.19	-0.52	1.00													
RMS SWA, straight	0.37	0.18	-0.26	0.66	1.00												
RMS SWA, curves	-0.14	-0.39	-0.30	0.57	0.53	1.00											
RMS FWA, overtaking	0.19	-0.16	-0.53	0.98	0.70	0.55	1.00										
RMS FWA, straight	0.37	0.18	-0.26	0.66	1.00	0.53	0.70	1.00									
RMS FWA, curves	-0.14	-0.41	-0.31	0.58	0.52	1.00	0.56	0.52	1.00								
RMS SWV, overtaking	0.13	-0.18	-0.54	0.95	0.64	0.51	0.95	0.64	0.52	1.00							
RMS SWV, straight	0.17	0.08	-0.35	0.57	0.87	0.58	0.60	0.87	0.57	0.62	1.00						
RMS SWV, curves	-0.33	-0.18	-0.27	0.57	0.33	0.69	0.53	0.33	0.70	0.57	0.52	1.00					
Max absolute lateral error, straight	0.49	0.24	0.23	-0.03	0.31	0.03	0.01	0.31	0.01	-0.12	0.09	-0.32	1.00				
Max absolute lateral error, curves	0.54	0.12	0.37	0.09	0.31	0.09	0.08	0.31	0.08	-0.02	0.11	-0.07	0.50	1.00			
NASA-TLX overall	0.13	-0.16	0.14	0.27	0.13	-0.09	0.23	0.13	-0.07	0.24	-0.04	-0.04	0.03	0.01	1.00		
Steering system ranking	0.05	-0.02	0.00	-0.17	-0.08	-0.06	-0.19	-0.08	-0.06	-0.09	-0.08	-0.14	0.13	0.17	0.00	1.00	
Mileage	0.18	-0.27	0.11	-0.15	-0.35	0.05	-0.17	-0.35	0.06	-0.17	-0.40	0.03	0.09	0.29	-0.04	0.30	1.00
Weekly driving	0.19	0.08	-0.02	-0.23	-0.26	-0.16	-0.25	-0.26	-0.17	-0.24	-0.24	-0.10	-0.12	0.20	-0.13	0.14	0.47

Note: $p < 0.05$ for $|\rho| \geq 0.41$, $p < 0.01$ for $|\rho| \geq 0.52$ and $p < 0.001$ for $|\rho| \geq 0.63$

Table A.4: Spearman rank-order correlation matrix for Driver Initiated condition (N=24)

	Effort, overtaking	Effort, straight	Effort, curves	RMS SWA, overtaking	RMS SWA, straight	RMS SWA, curves	RMS FWA, overtaking	RMS FWA, straight	RMS FWA, curves	RMS SWV, overtaking	RMS SWV, straight	RMS SWV, curves	Max absolute lateral error, straight	Max absolute lateral error, curves	NASA-TLX overall	Steering system ranking	Mileage
Effort, overtaking	1.00																
Effort, straight	0.64	1.00															
Effort, curves	0.48	0.51	1.00														
RMS SWA, overtaking	-0.36	-0.35	-0.11	1.00													
RMS SWA, straight	-0.05	-0.14	-0.31	0.38	1.00												
RMS SWA, curves	0.00	-0.17	0.09	0.40	0.26	1.00											
RMS FWA, overtaking	-0.36	-0.19	-0.15	0.81	0.39	0.17	1.00										
RMS FWA, straight	-0.12	-0.12	-0.31	0.29	0.88	0.19	0.42	1.00									
RMS FWA, curves	-0.35	-0.29	-0.26	0.35	0.35	0.52	0.22	0.41	1.00								
RMS SWV, overtaking	-0.36	-0.26	-0.14	0.92	0.39	0.40	0.91	0.39	0.26	1.00							
RMS SWV, straight	-0.10	-0.18	-0.27	0.48	0.90	0.45	0.42	0.84	0.42	0.52	1.00						
RMS SWV, curves	-0.23	-0.28	-0.13	0.66	0.40	0.78	0.42	0.30	0.63	0.61	0.58	1.00					
Max absolute lateral error, straight	0.18	0.10	0.00	-0.19	0.08	0.23	-0.20	0.09	0.22	-0.14	0.01	-0.07	1.00				
Max absolute lateral error, curves	-0.01	0.18	-0.07	-0.23	0.26	0.06	-0.10	0.31	0.43	-0.26	0.03	-0.12	0.46	1.00			
NASA-TLX overall	0.13	0.12	0.37	0.03	-0.20	-0.07	0.18	-0.32	-0.28	0.08	-0.20	-0.14	0.01	-0.23	1.00		
Steering system ranking	-0.04	-0.15	0.24	0.17	0.08	0.30	0.08	0.16	0.16	0.12	0.06	0.20	-0.15	0.00	-0.05	1.00	
Mileage	-0.11	-0.32	-0.20	0.04	-0.26	-0.04	-0.06	-0.23	0.28	-0.09	-0.30	0.04	0.19	0.09	-0.20	-0.29	1.00
Weekly driving	0.09	0.02	-0.06	-0.03	-0.16	-0.12	-0.05	-0.17	-0.22	-0.10	-0.18	-0.12	-0.29	-0.10	-0.25	-0.21	0.47

Note: $p < 0.05$ for $|\rho| \geq 0.41$, $p < 0.01$ for $|\rho| \geq 0.52$ and $p < 0.001$ for $|\rho| \geq 0.63$

B
Extended results

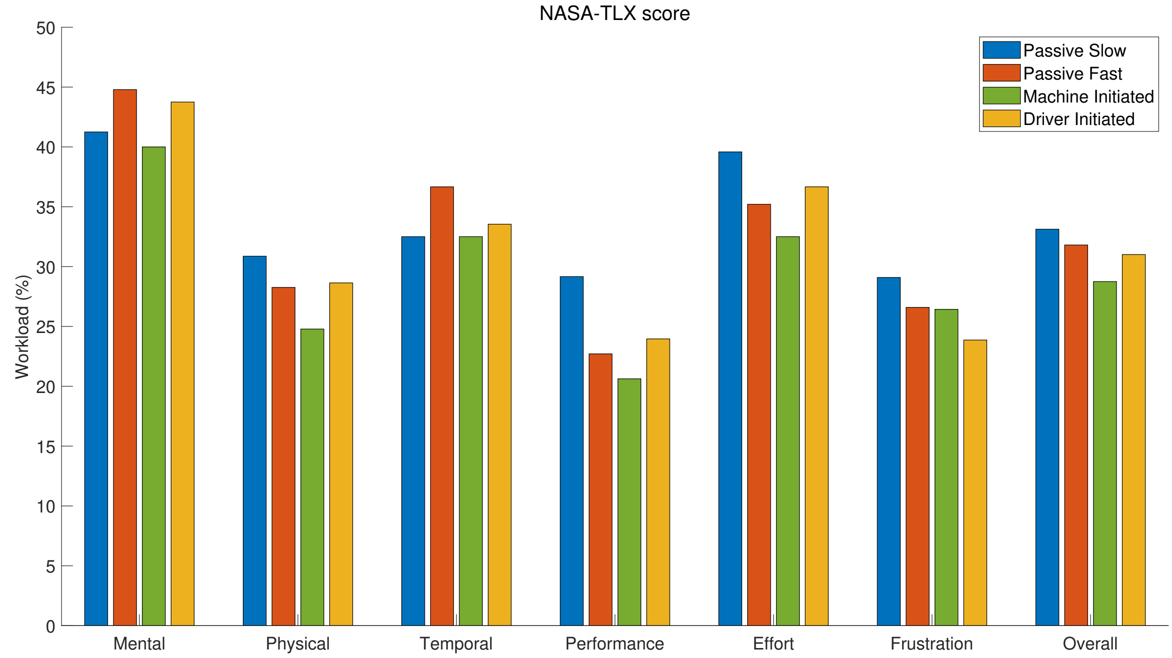

Figure B.1: Mean scores on the NASA-TLX.
NASA-TLX Performance: PS-PF $p < 0.05$

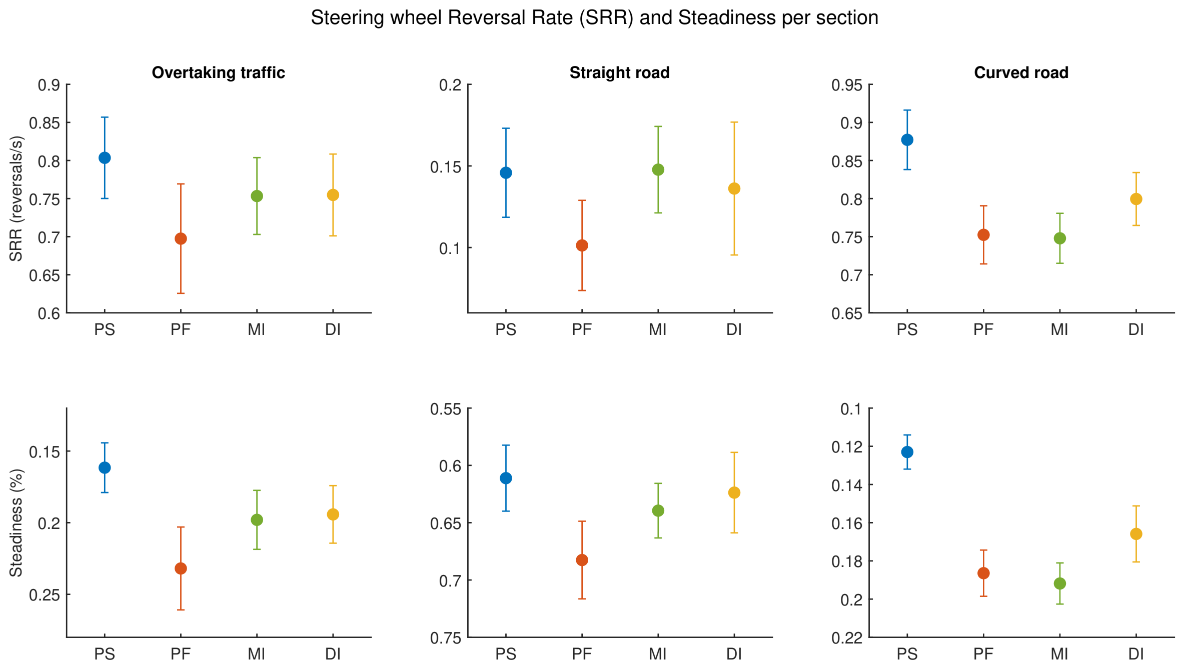

Figure B.2: Steering wheel reversal rate (top figures) and Steering wheel steadiness (bottom figures) per condition and per section. Means and within-subject 95% CI are shown.
SRR Straight road: PS-PF and PF-MI $p < 0.05$
SRR Curved road: PS-PF and PS-MI $p < 0.01$, PS-DI $p < 0.05$
Steadiness Overtaking: PS-PF $p < 0.01$ and PS-MI $p < 0.05$
Steadiness Straight road: PS-PF $p < 0.01$
Steadiness Curved road: PS-PF, PS-MI and PS-DI $p < 0.001$

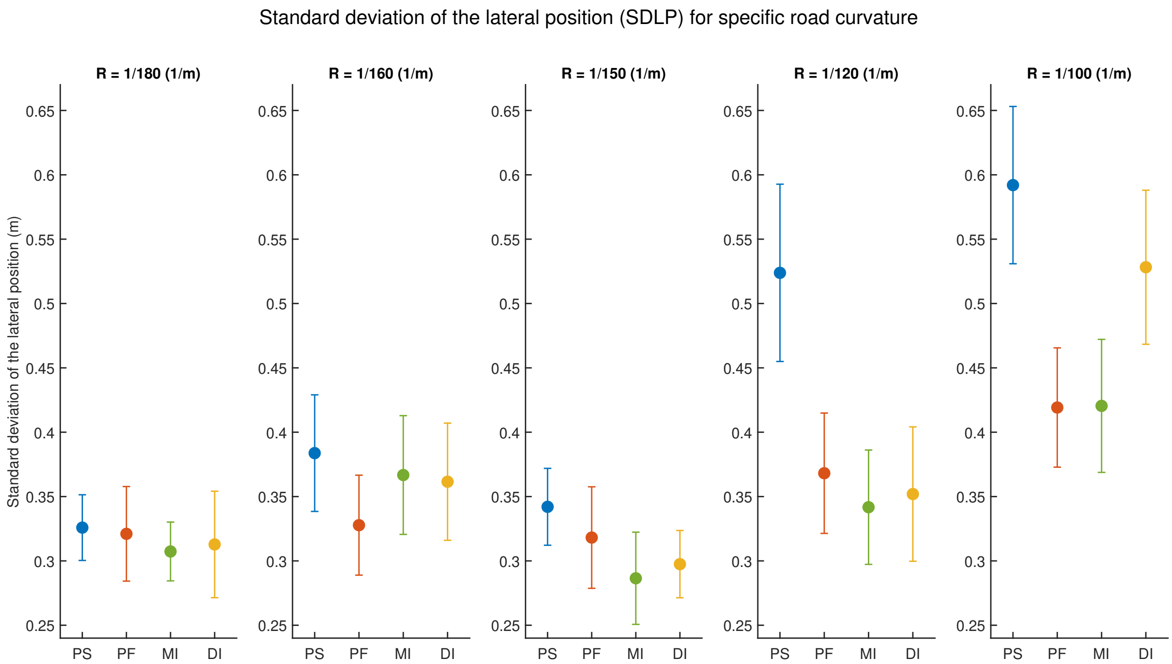

Figure B.3: Standard deviation of the lateral position (SDLP) per condition for five driven road curvatures. Means and within-subject 95% CI are shown.

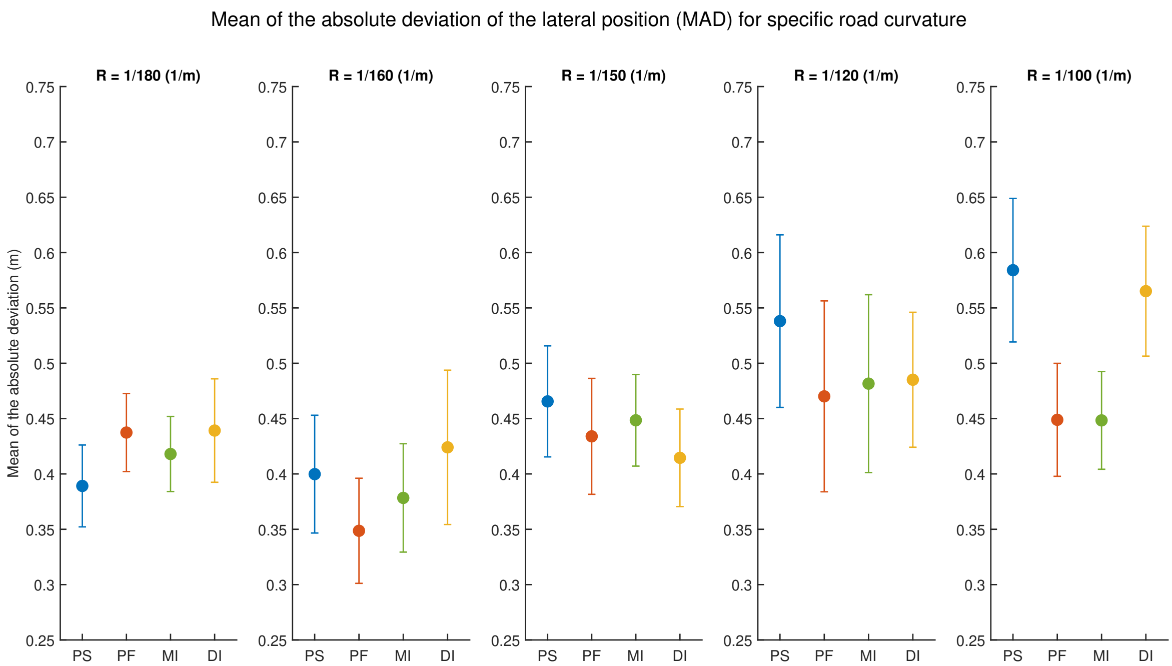

Figure B.4: Mean of the absolute deviation (MAD) per condition for five driven road curvatures. Means and within-subject 95% CI are shown.

C

Informed Consent Form

Informed Consent Form in a driving simulator study

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This document describes the purpose, procedures, benefits, risks and possible discomforts of a driving simulator study. It also describes the right to withdraw from the study at any time in any case. Before agreeing to participate in this study, it is important that the information provided in this document is fully read and understood.

Location of the experiment
TU Delft, Faculty of Mechanical, Maritime and Materials Engineering (3mE)
Cognitive Robotics Lab (F-0-220)
Mekelweg 2, 2628CD Delft

Purpose of the study: The purpose of this study is to look into the effect of changing steering ratio's initiated by the driver (you) or the machine itself. Two steering ratio settings (a slow steering and a fast steering mode) are tested in a machine-initiated steering system and a human-initiated steering system (where the driver can adapt the steering modes) and the designs are compared with two different passive steering system (passive slow steering and passive fast steering). The effect of these systems is measured in terms of performance, safety margins, driver workload and system acceptance. The results will be statistically analysed and published in a Master thesis.

Procedure: You will be requested to take place in the driving simulator (fixed-base driving simulator) and you will be briefed how to operate it. The simulator car has a constant speed, so only the steering wheel needs to be controlled. You are requested to keep both hands on the steering wheel in a ten-to-two position at all time.

The experiment consists of driving one trial with each of the four conditions i.e. Passive-Slow, Passive-Fast, Machine-initiated and Human-initiated. In the machine-initiated condition the steering ratio will be changed for you to assist the driver in different traffic/road situations. In the human-initiated condition the steering ratio can be changed by you by clicking on a mouse button. By clicking the upper button the steering ratio increases (fast steering) and by clicking the lower button the steering ratio decreases (slow steering).

First, you will drive for five minutes on a road to become familiar with the vehicle and the steering dynamics. Prior to each trial, you will drive a test trial with each of the four conditions to become familiar with the specific steering system (one of the four conditions). During the real trials you are asked to drive as you normally would with the emphasis on safe and controlled driving. The test track consists of three sections i.e. overtaking traffic vehicles which have a constant speed on a straight road, following a straight road without traffic vehicles and following a curved road without traffic vehicles. After the experiment you are asked to fill out a questionnaire.

Task instructions: During the entire track drive as you normally would. You are expected to drive on the right-lane unless the traffic situation requires you to drive on the left-lane.

Duration: The total experiment, including filling out a questionnaire and participating in the interview after the experiment, will take approximately 1 hour.

Risk and discomforts: Virtual environments like driving simulators can cause different types of sicknesses: visuomotor dysfunctions (eyestrain, blurred vision, difficulty focusing), nausea, drowsiness, fatigue, or headache. These symptoms are similar to motion sickness. If you feel uncomfortable in any way during the experiment, you are advised to stop the experiment or rest for several minutes. If you do not feel well, please take sufficient rest before leaving the laboratory.

Confidentiality: The collected data in this experiment is kept confidential and will be used for research purposes only. The data will also be anonymised i.e. you will be identified by a subject number.

Right to refuse or withdraw: Your participation is strictly voluntary and you may withdraw from or stop this experiment at any time, without consequences.

Questions: If you have any questions regarding this experiment, feel free to contact M. Weijerman (contact details are provided at the top of this document).

Additional information regarding COVID-19: To prevent the spread of the corona virus (in compliance with the university's policy), researchers and participants in the study:

- have to be younger than 70 years
- don't have any underlying ailments that could be seen as a riskfactor for a COVID-19 infection
- don't have any complaints or symptoms that could be indicative of a COVID-19 infection
- have not been in contact with a COVID-19 patient at least 14 days before participation in the study
- take suitable protective measures if a minimum distance of 1.5 meters is not viable
- are enabled to travel outside of rush hours to and from the research location

Also, any objects or surfaces researchers and participants come into contact will be disinfected prior and after use.

I have read and understood the information provided above.
I give permission to process the data for the purpose described above.
I voluntary agree to participate in this study.

Name of the participant:

Signature: **Date:**

D
Questionnaires

D.1. Generic driving experience questionnaire

Generic driving experience questionnaire

1. Participant ID

____

2. What is your age?

____

3. What is your gender?

Markeer slechts één ovaal.

- ⬭ Male
- ⬭ Female
- ⬭ I prefer not to answer
- ⬭ Anders: ______________________________

4. What is your primary mode of transportation?

Markeer slechts één ovaal.

- ⬭ Automobile
- ⬭ Motorcycle
- ⬭ Public transportation
- ⬭ Human powered transportation (walking, cycling)
- ⬭ I prefer not to answer
- ⬭ Anders: ______________________________

5. On average, how often did you drive a vehicle in the last months?

Markeer slechts één ovaal.

- Every day
- 4-6 days a week
- 1-3 days a week
- Less than once a week
- Less than once a month
- Never
- I prefer not to answer

6. Roughly how many kilometers did you drive in the last 12 months?

Markeer slechts één ovaal.

- 0 km
- 1 - 1000 km
- 1000 - 5000 km
- 5000 - 10000 km
- 10000 - 15000 km
- 15000 - 20000 km
- 20000 - 30000 km
- More than 30000 km
- I prefer not to answer

7. Have you ever driven a vehicle with different driving modes (e.g. comfort mode, sport mode, eco mode) and if yes, how often do you use these different modes?

Markeer slechts één ovaal.

- Yes, I use different driving modes every time I drive.
- Yes, I use different driving modes most of the time when I drive.
- Yes, I use different driving modes sometimes when I drive.
- Yes, I rarely use different driving modes when I drive.
- Yes, but I don't use different driving modes when I drive.
- No, I have never driven a vehicle with different driving modes.
- I prefer not to answer

8. (Only if you use different driving modes): please motivate why you switch between driving modes

D.2. Post-trial questionnaires

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Nausea: To what extend do you experience nausea? Please circle the statement that is most fitting to your condition:

1. Not experiencing any nausea, no sign of symptoms.
2. Arising symptoms (like a feeling in the abdomen), but no nausea.
3. Slightly nauseous
4. Nauseous.
5. Very nauseaous, retching.
6. Throwing up.

Participant ID: Condition:

During the test, it took me little effort to overtake the traffic vehicles:

Disagree Neutral Fully agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

During the test, it took me little effort to follow the lane on the straight road:

Disagree Neutral Fully agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

During the test, it took me little effort to follow the lane on the curved road:

Disagree Neutral Fully agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

D.3. Post-experiment questionnaire

Post-experiment questionnaire Participant ID:

When overtaking the traffic vehicles I prefer the slow steering response:

Disagree Neutral Fully agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

When driving on a straight road I prefer the slow steering response:

Disagree Neutral Fully agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

When driving on a curved road I prefer the slow steering response:

Disagree Neutral Fully agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

The adaptations by the machine where useful for the traffic/driving situation:

Disagree Neutral Fully agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

During human-initiated steering, the advice (red arrow) affected my choice of the steering mode:

Disagree Neutral Fully agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

Which steering system do you prefer? Rank the four systems from 1 to 4 (1 most, 4 least).

Passive-Slow: Passive-Fast: Machine-initiated: Human-initiated:

Do you prefer letting the machine change the steering modes or changing the steering modes

yourself (MI vs HI)? Machine-initiated : ☐ Human-initiated: ☐

E

Traffic vehicles

Traffic vehicle #	Driving lane	Start position on the road (m)	Distance to traffic vehicle ahead (m)	Vehicle density (vehicles/km)
1	right	215	80	12.5
2	left	295	75	13.33
3	right	370	70	14.29
4	left	440	65	15.38
5	right	505	60	16.67
6	left	565	55	18.18
7	right	620	50	20
8	left	670	45	22.22
9	right	715	40	25
10	left	755	40	25
11	right	795	40	25
12	left	835	40	25
13	right	875	40	25
14	left	915	40	25
15	right	955	40	25
16	left	995	40	25
17	right	1035	40	25
18	left	1075	40	25
19	right	1115	40	25
20	left	1155	40	25
21	right	1195	40	25
22	left	1235	40	25
23	right	1275	40	25
24	left	1315	40	25
25	right	1355	45	22.22
26	left	1400	50	20
27	right	1450	55	18.18
28	left	1505	60	16.67
29	right	1565	65	15.38
30	left	1630	70	14.29
31	right	1700	75	13.33
32	left	1775	80	12.5
33	right	1855	0	0

Table E.1: Traffic vehicle data: driving lane of the traffic vehicles on the road, the distance compared to the start position of the driver, the distance compared to each other and the calculated traffic density at each point. Traffic vehicles have a constant velocity of 60 km/h, distance between the traffic vehicles stays the same.

F

Order of conditions per participant

Participant #	Trial 1	Trial 2	Trial 3	Trial 4
1	PS	PF	MI	DI
2	PS	DI	PF	MI
3	PF	DI	PS	MI
4	DI	PS	MI	PF
5	PS	MI	DI	PF
6	DI	PF	PS	MI
7	MI	PF	PS	DI
8	PF	MI	PS	DI
9	PF	PS	DI	MI
10	MI	PS	DI	PF
11	PS	DI	MI	PF
12	MI	PS	PF	DI
13	PS	MI	PF	DI
14	DI	MI	PF	PS
15	PF	DI	MI	PS
16	PF	PS	MI	DI
17	DI	PF	MI	PS
18	MI	DI	PS	PF
19	DI	MI	PS	PF
20	MI	DI	PF	PS
21	PF	MI	DI	PS
22	MI	PF	DI	PS
23	PS	PF	DI	MI
24	DI	PS	PF	MI

Table F.1: Order of the conditions for 24 participants and 4 trials. Order of the conditions is fully counterbalanced over the participants. PS = Passive Slow, PF = Passive Fast, MI = Machine Initiated, DI = Driver Initiated

G

Subjective data per participant

Participant #	Overtaking traffic				Straight road				Curved road			
	PS	PF	MI	DI	PS	PF	MI	DI	PS	PF	MI	DI
1	5	3	5	1	1	1	1	1	5	3	2	3
2	2	4	3	2	1	2	2	1	3	3	2	3
3	1	2	1	1	1	1	1	1	3	3	2	3
4	2	1	1	1	1	2	1	1	3	2	3	4
5	1	1	1	1	1	1	1	1	1	1	1	1
6	2	3	3	4	2	2	2	2	4	3	3	3
7	5	2	1	2	4	4	1	2	7	4	4	6
8	2	2	2	2	1	1	1	1	2	5	3	2
9	1	1	1	1	1	1	1	1	2	2	1	1
10	1	1	1	1	1	2	1	1	2	1	1	1
11	3	1	3	2	1	3	1	1	5	1	2	2
12	6	2	2	2	2	4	2	2	5	5	2	5
13	5	2	4	1	1	5	2	2	6	3	3	3
14	2	1	1	1	1	1	1	1	3	3	3	3
15	2	2	2	2	3	2	3	3	4	3	3	3
16	2	2	1	1	1	5	1	1	6	4	2	2
17	5	5	3	4	2	6	3	5	5	5	3	4
18	2	2	2	2	2	2	2	2	4	2	2	3
19	2	2	2	6	1	1	1	2	4	2	3	5
20	2	2	3	1	1	1	1	1	2	2	2	2
21	2	2	2	2	2	2	2	2	4	3	2	4
22	3	2	2	2	1	1	2	2	3	2	3	2
23	2	1	1	1	1	2	1	2	4	2	2	2
24	1	1	7	1	1	1	1	1	3	1	1	3

Perceived effort per section on a seven-point scale

Table G.1: The perceived effort per section, condition and participant on a seven-point scale (1 = low effort, 7 = high effort).

Post-experiment questionnaire results										
Participant #	Preferred steering response			Steering system ranking:				Preference	Usefulness	Effect
	Overtaking	Straight	Curves	PS	PF	MI	DI	MI/DI adaptation	MI-adaptation	advice
1	2	1	7	4	3	1	2	0	6	3
2	2	1	4	1	3	4	2	1	2	2
3	2	1	6	2	4	1	3	0	6	4
4	3	1	5	2	3	4	1	1	4	3
5	7	1	7	3	2	1	4	0	7	7
6	5	2	6	4	2	3	1	1	5	3
7	2	3	7	4	3	1	2	0	7	2
8	3	1	4	2	3	4	1	1	3	6
9	7	1	7	3	2	4	1	1	3	3
10	2	2	6	4	3	2	1	1	6	4
11	6	1	6	4	3	1	2	0	7	7
12	6	1	5	3	4	1	2	0	6	6
13	7	1	7	4	2	3	1	1	3	2
14	7	2	7	4	1	3	2	1	3	3
15	5	1	6	4	3	1	2	0	6	3
16	2	1	7	3	4	1	2	0	7	4
17	4	2	6	3	4	1	2	0	6	6
18	6	1	7	4	2	3	1	1	6	6
19	3	1	5	3	4	1	2	0	6	5
20	5	2	5	3	4	1	2	1	5	5
21	6	3	7	4	2	1	3	0	5	5
22	5	1	6	4	2	3	1	1	5	5
23	5	1	6	4	3	2	1	1	6	3
24	7	1	7	2	1	4	3	1	1	7

Table G.2: Post-experiment questionnaire results per participant: preferred steering response per section (1 = slow steering response, 7 = fast steering response), preferred steering system (1 = most preferred, 4 = least preferred), preference for machine- or driver-initiated adaptation (0 = MI, 1 = DI), how useful were the machine-initiated adaptations (1 = not useful, 7 = very useful), effect of the advice on the choice of the steering response during driver-initiated steering (1 = not affected, 7 = affected).

G.3. Generic driving experience questionnaire open answer

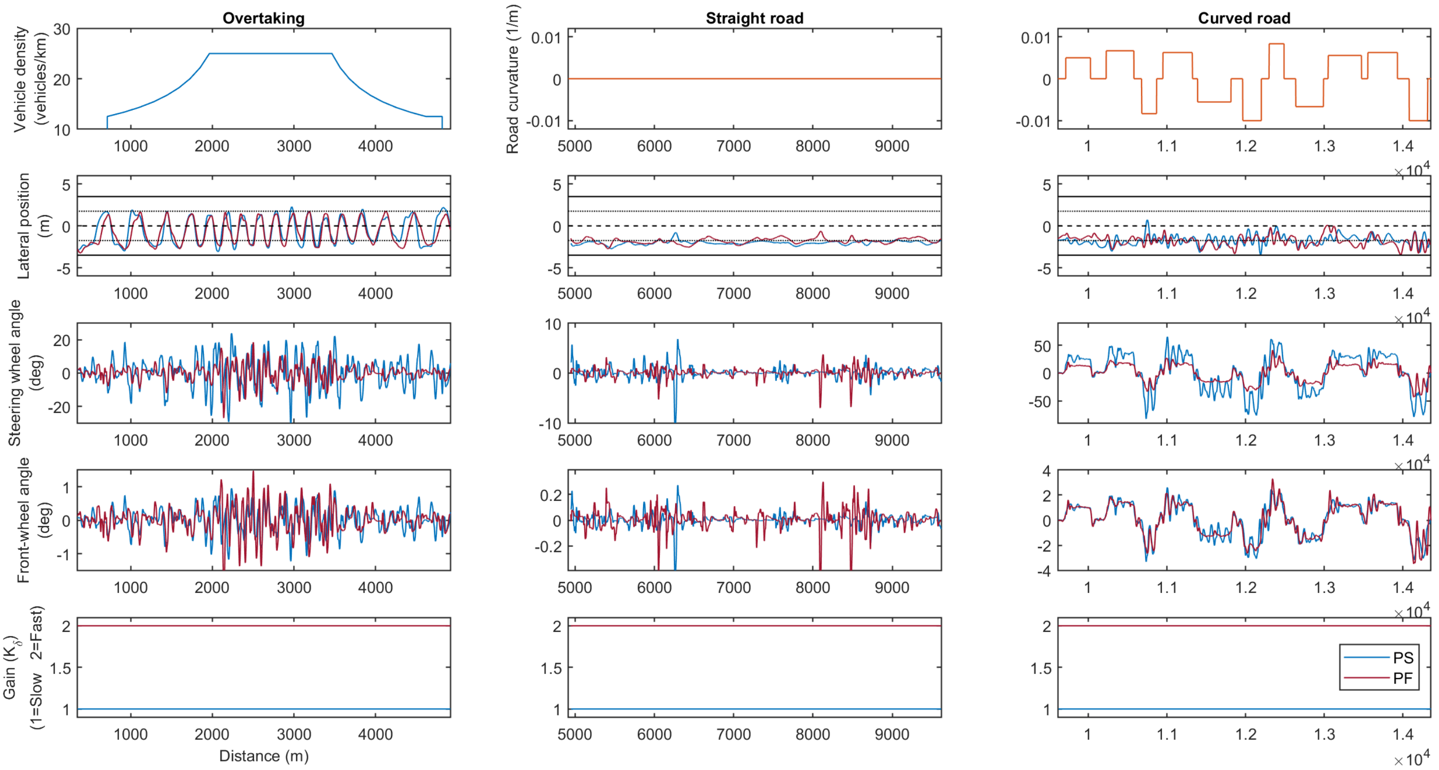
If you use different driving modes, please motivate why you switch between driving modes.

- When I drive in the mountains I sometimes use the sport mode.
- If I need more power I switch from eco to normal/powermode.
- Faster accelaration or more comfortable gear changes.
- Eco mode, because it is burning less fuel.
- It is or by accident or if the road is almost totally empty and I have space to practice it.
- To try the differences.
- Switch from comfort to sport mode when there is a setting in which I can have some fun with my father's car.
- On the highway comfort mode is nicer to drive and on country roads sport mode is nicer to drive.
- Ecomode for long stretches and to save gas.

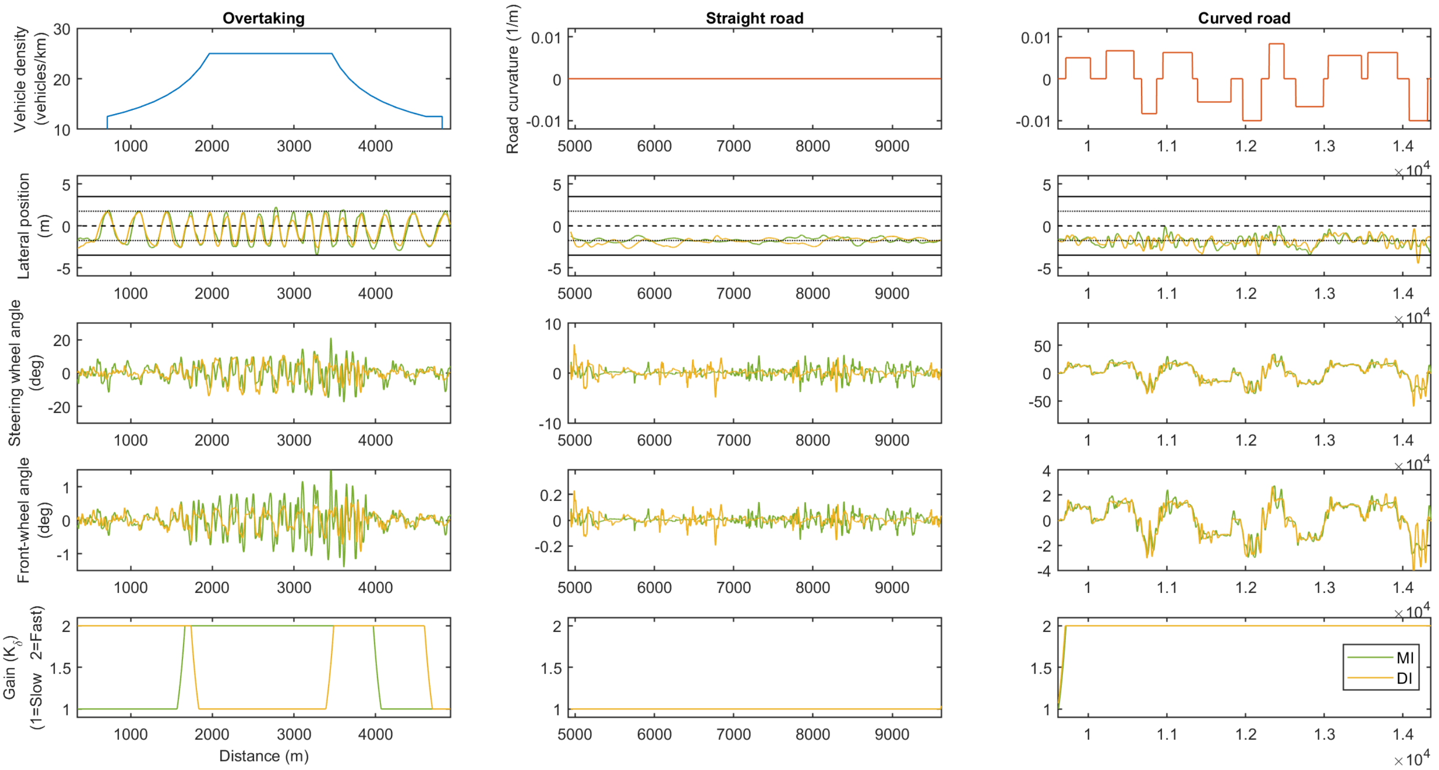
H

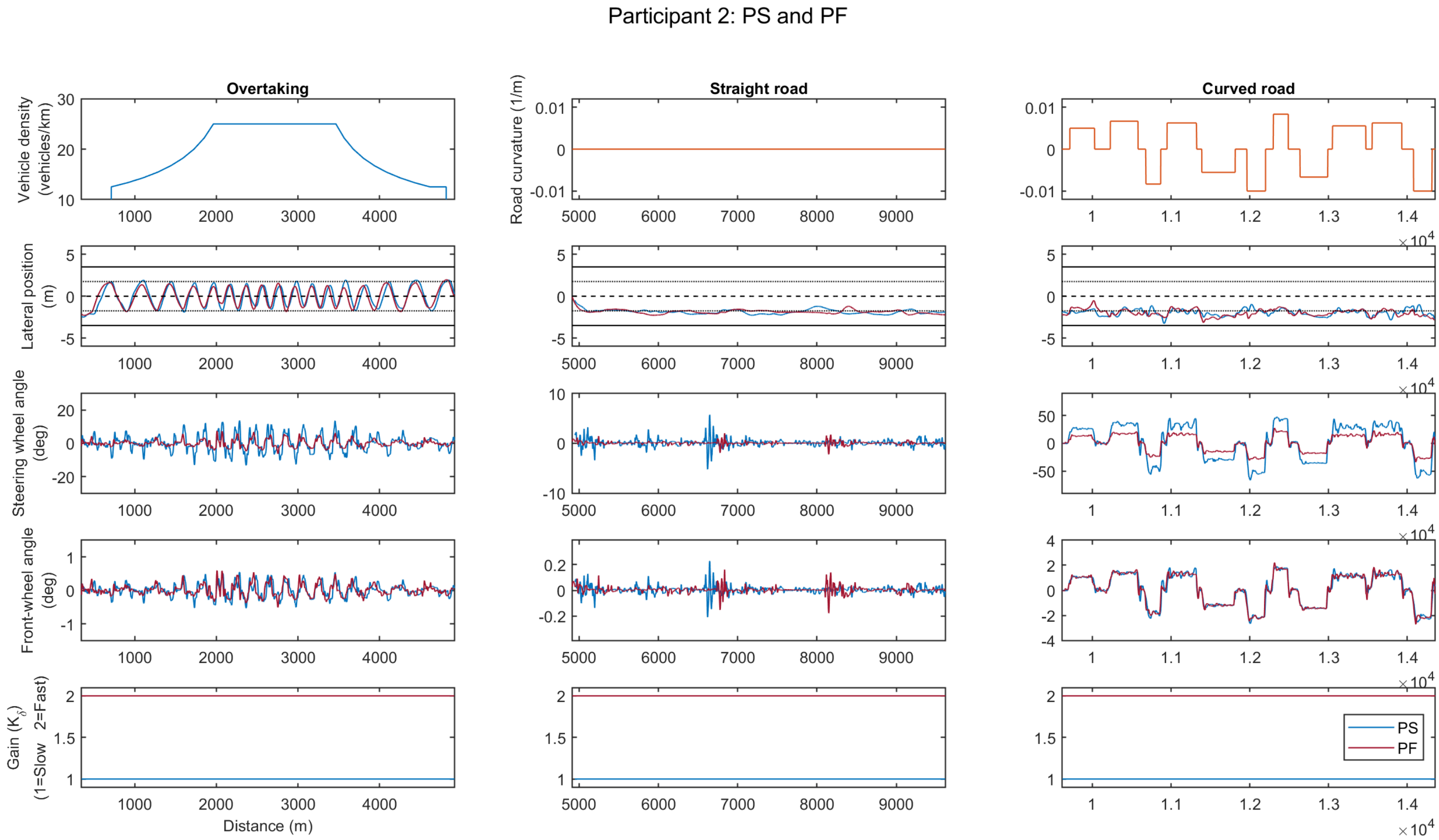
Figure for each participant

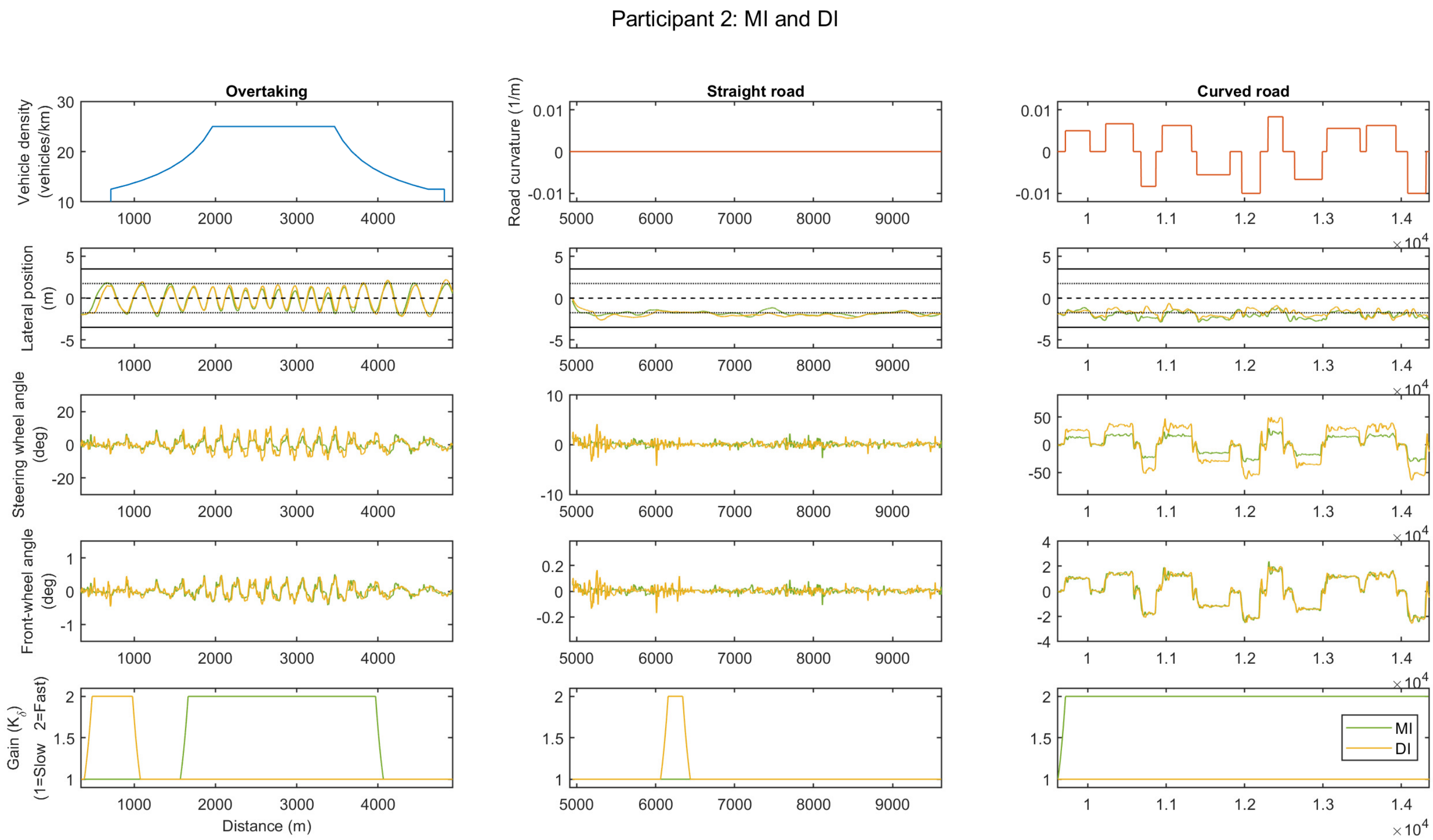
Participant 1: PS and PF



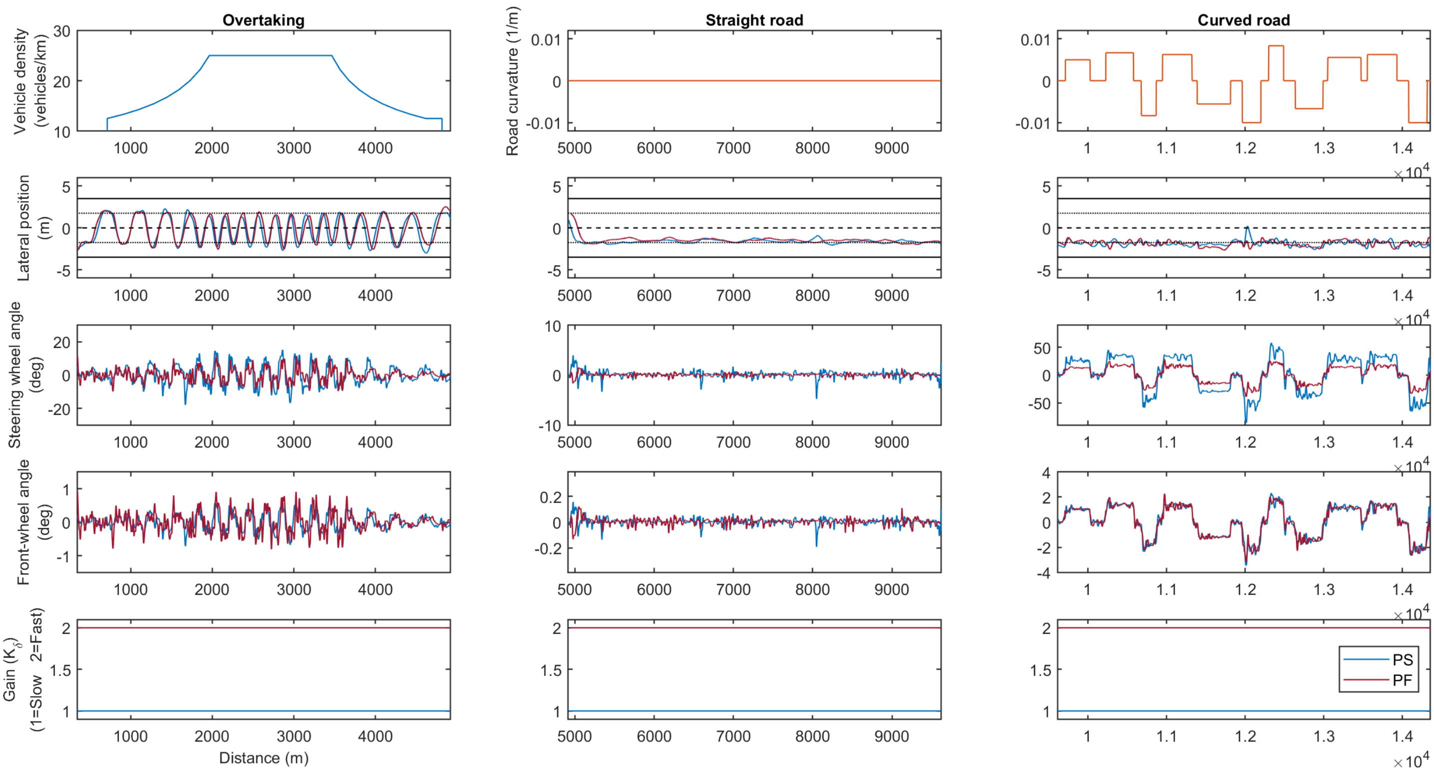
Participant 1: MI and DI



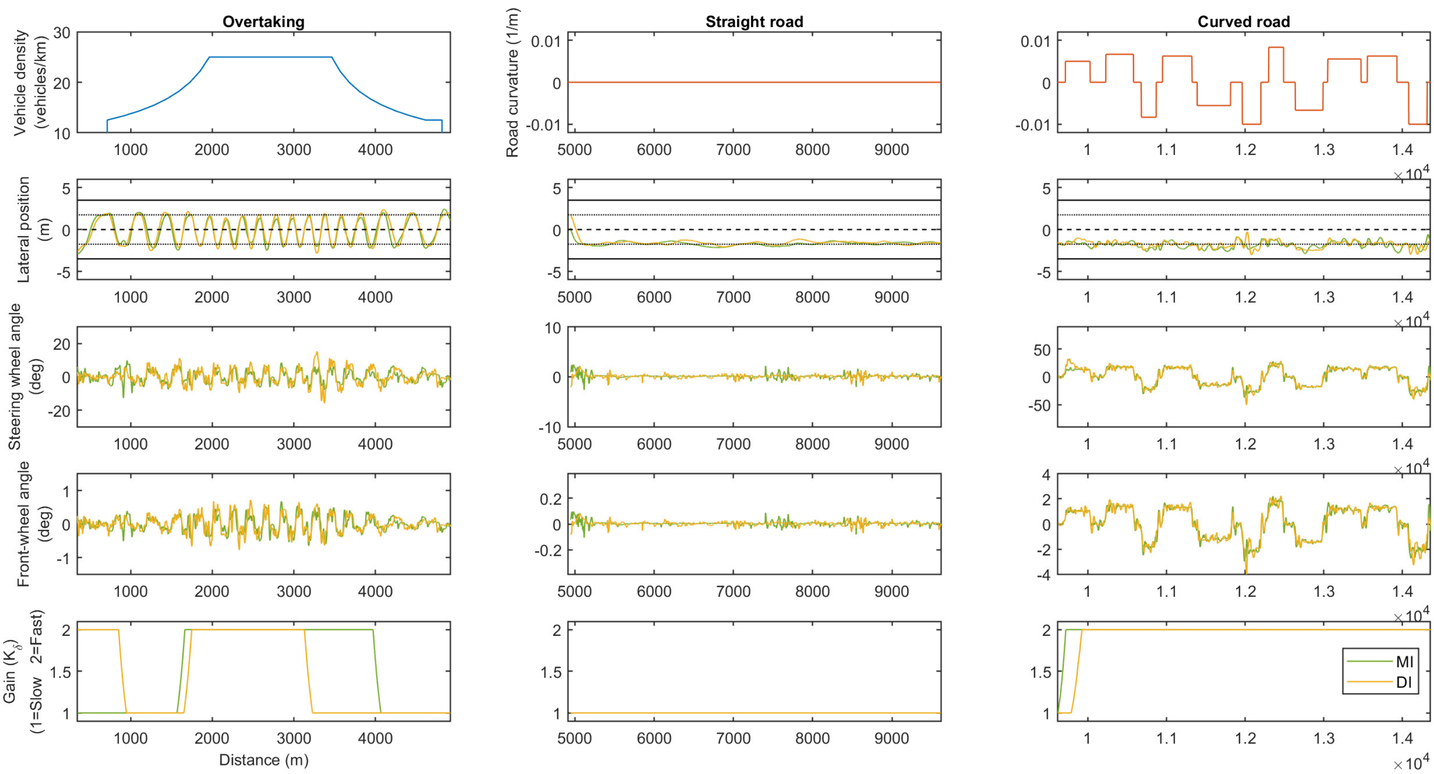

Participant 2: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF

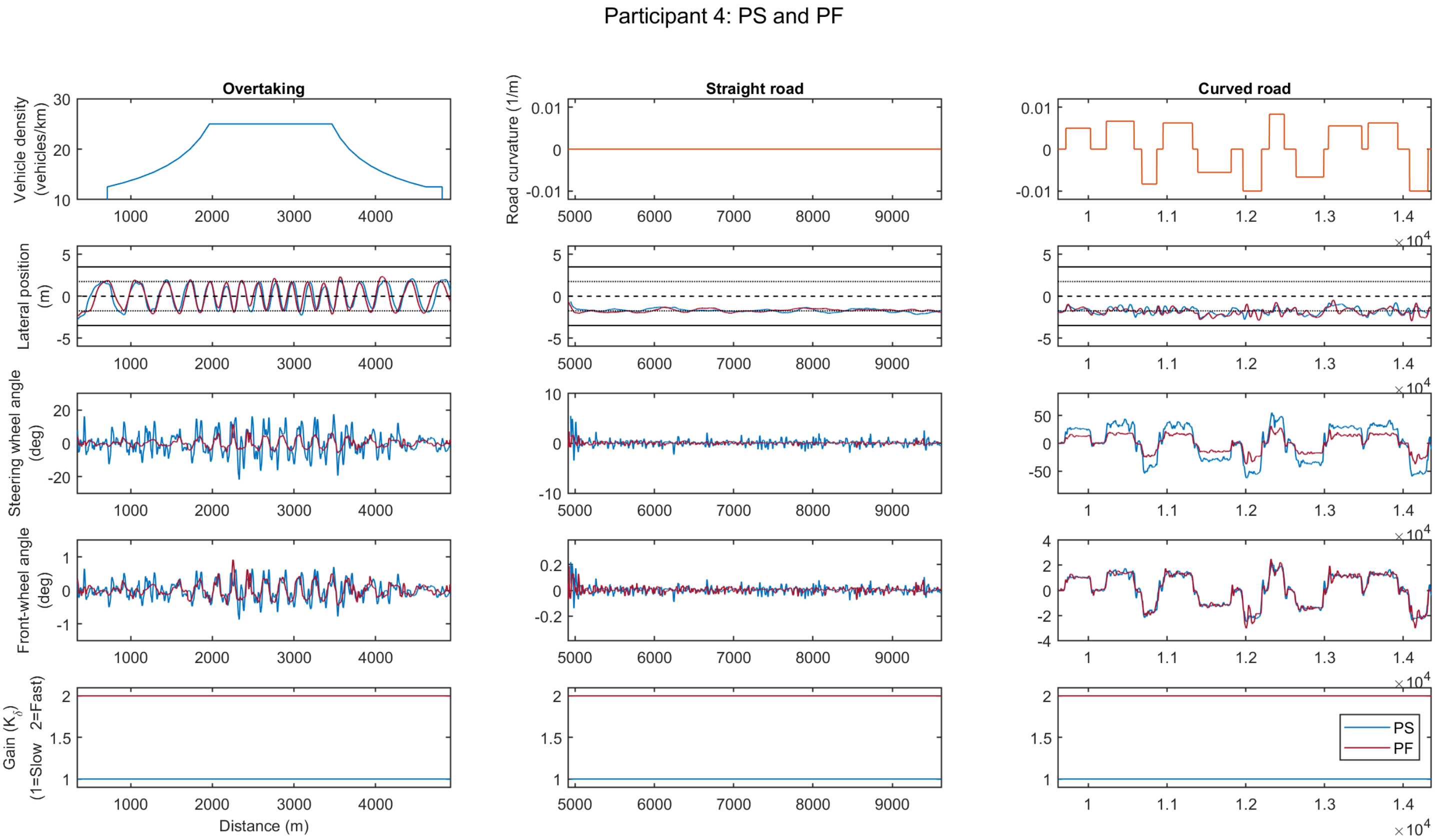

Participant 2: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI

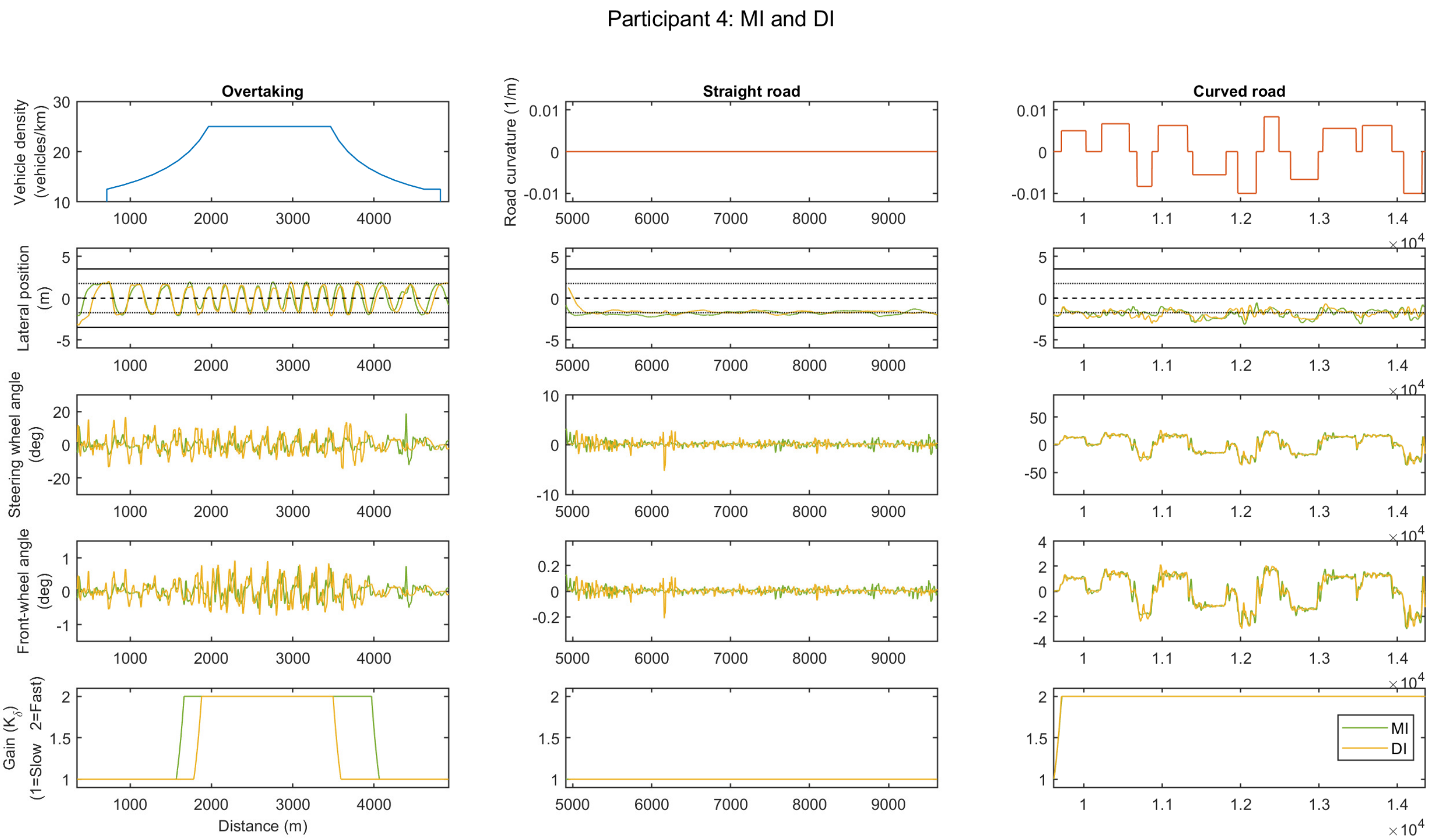
Participant 3: PS and PF

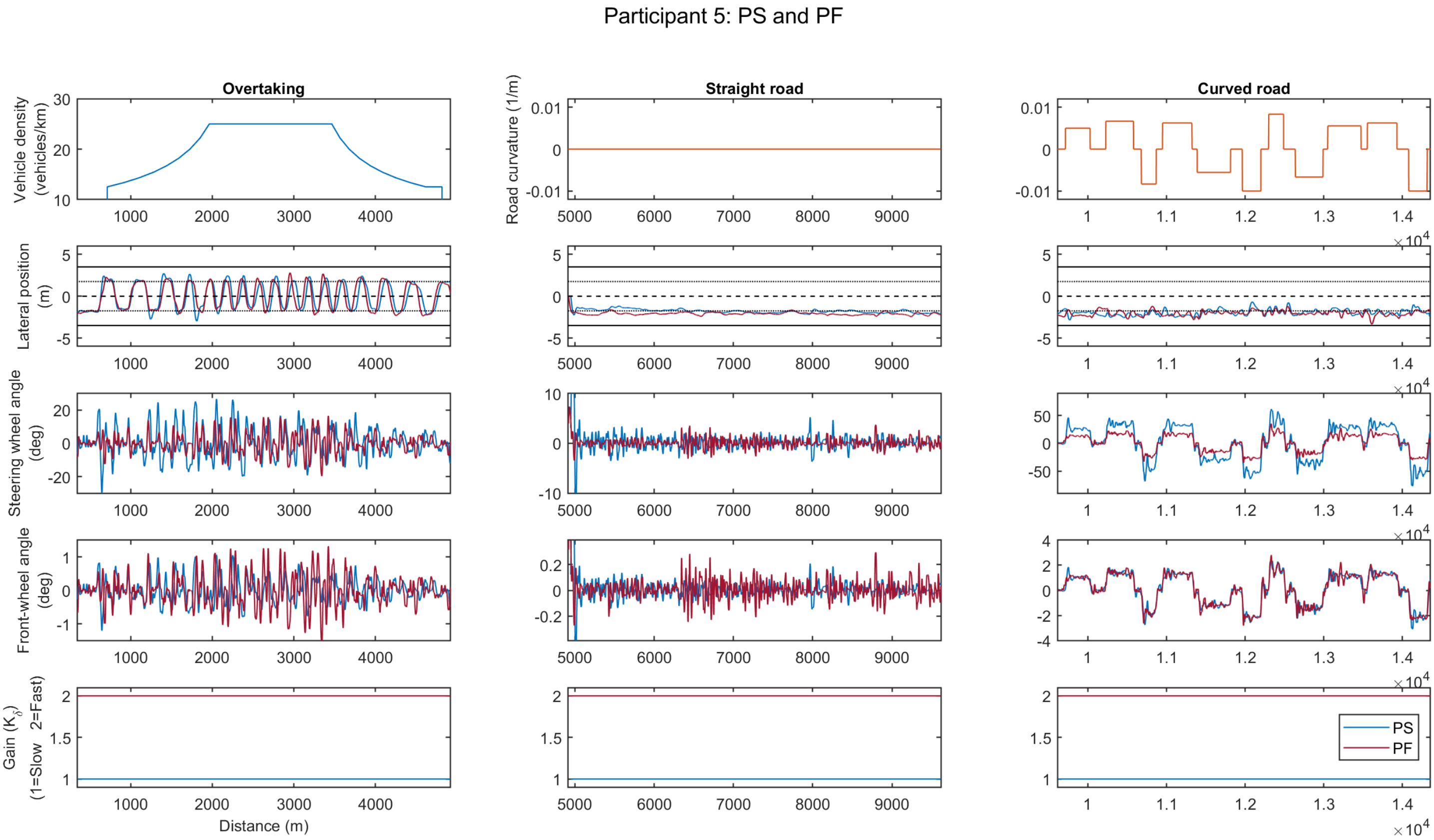


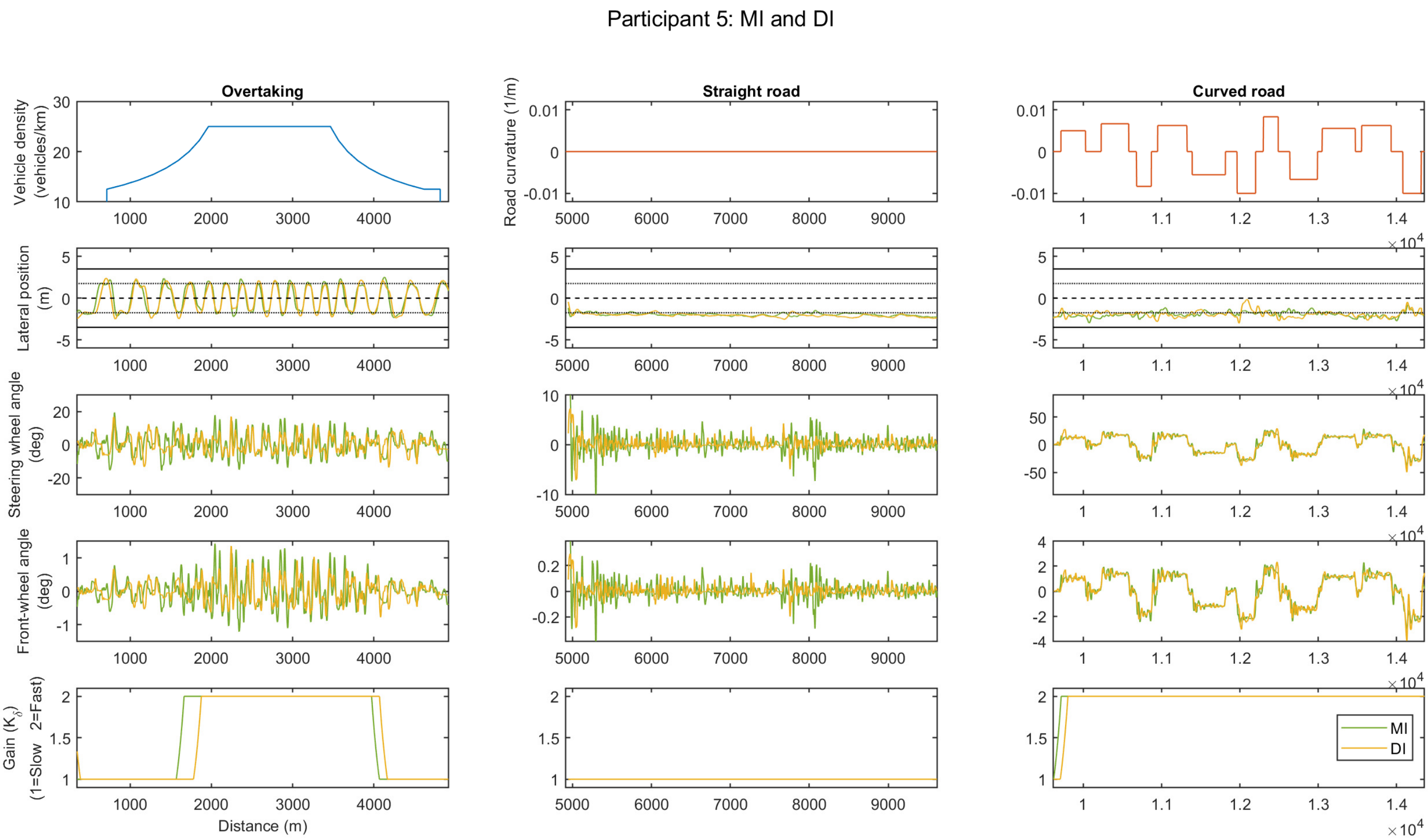
Participant 3: MI and DI



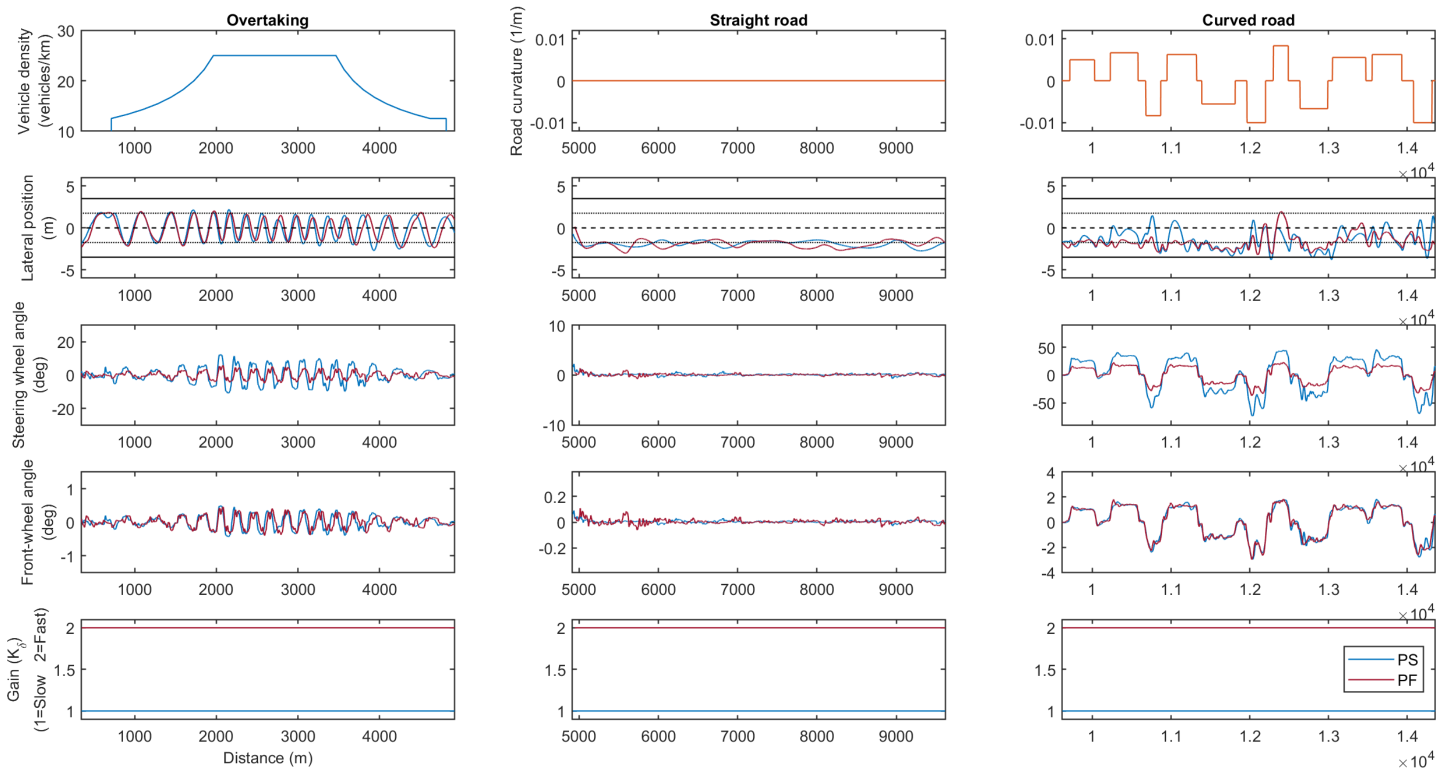

Participant 4: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF


Participant 4: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI

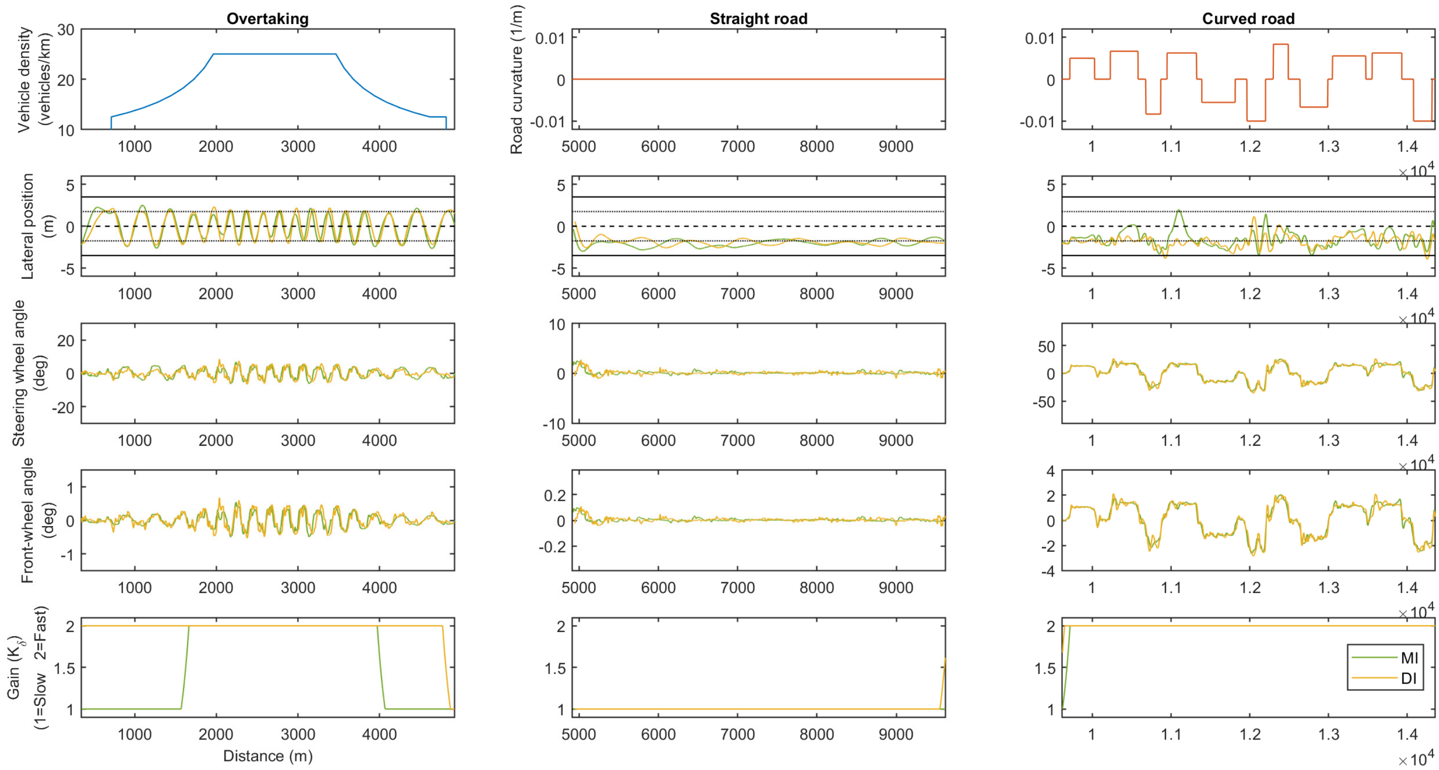

Participant 5: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF


Participant 5: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI

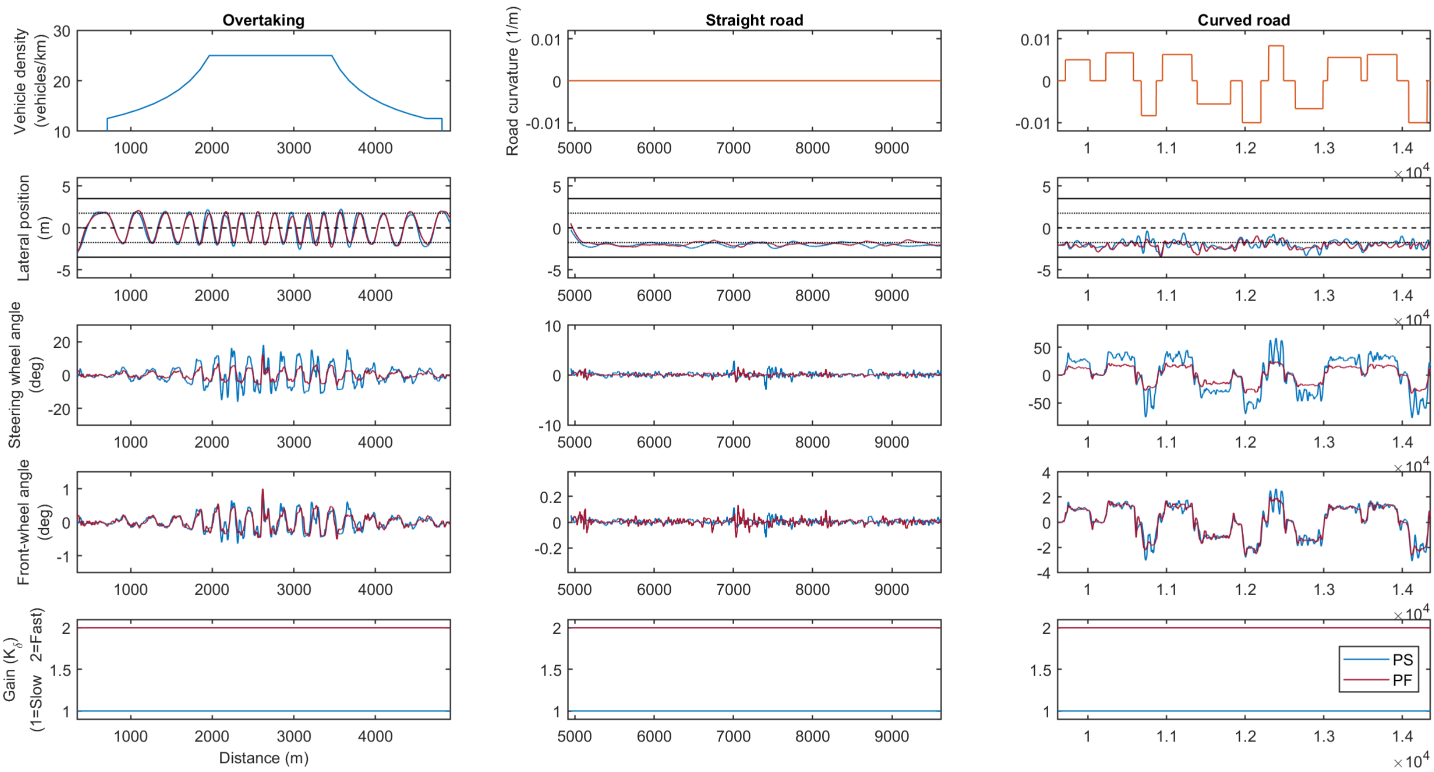
Participant 6: PS and PF



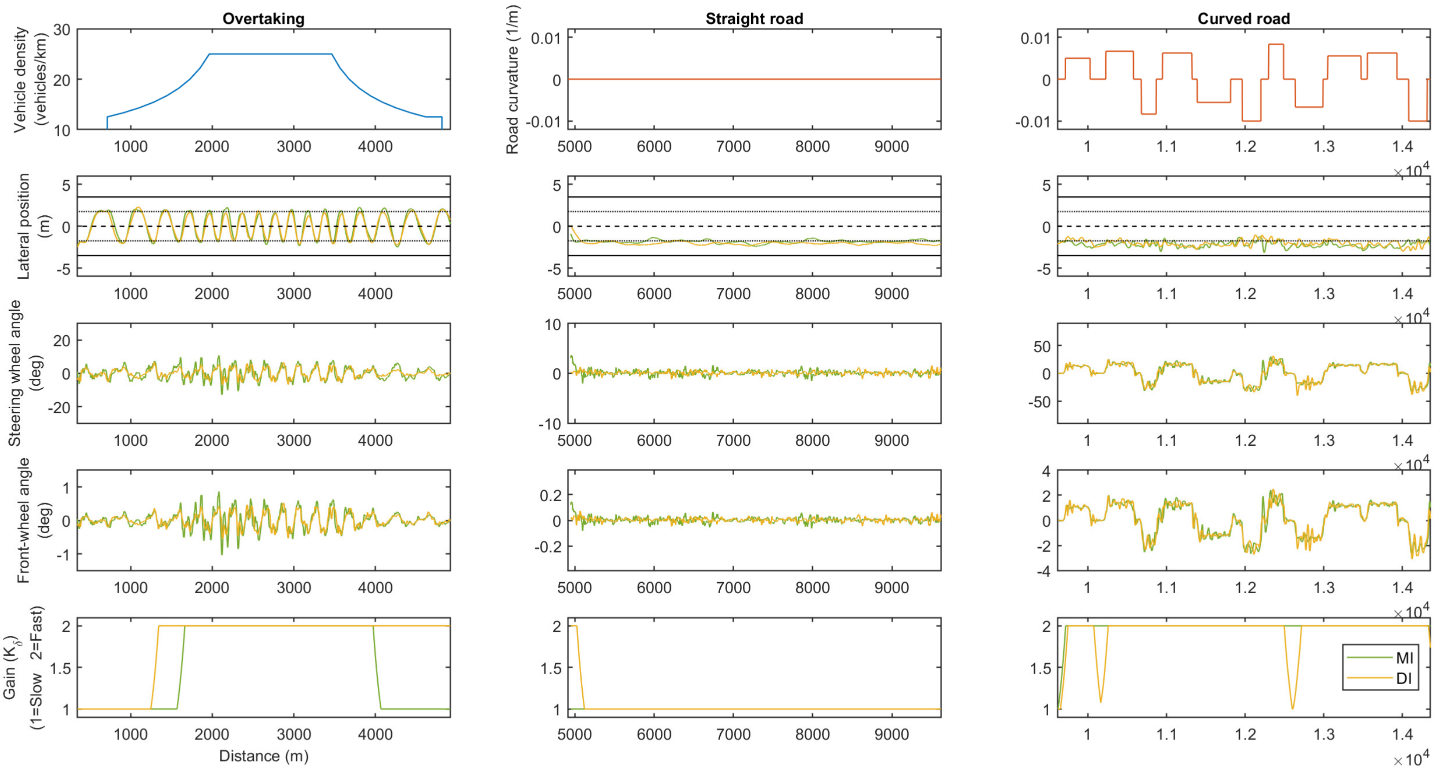
Participant 6: MI and DI

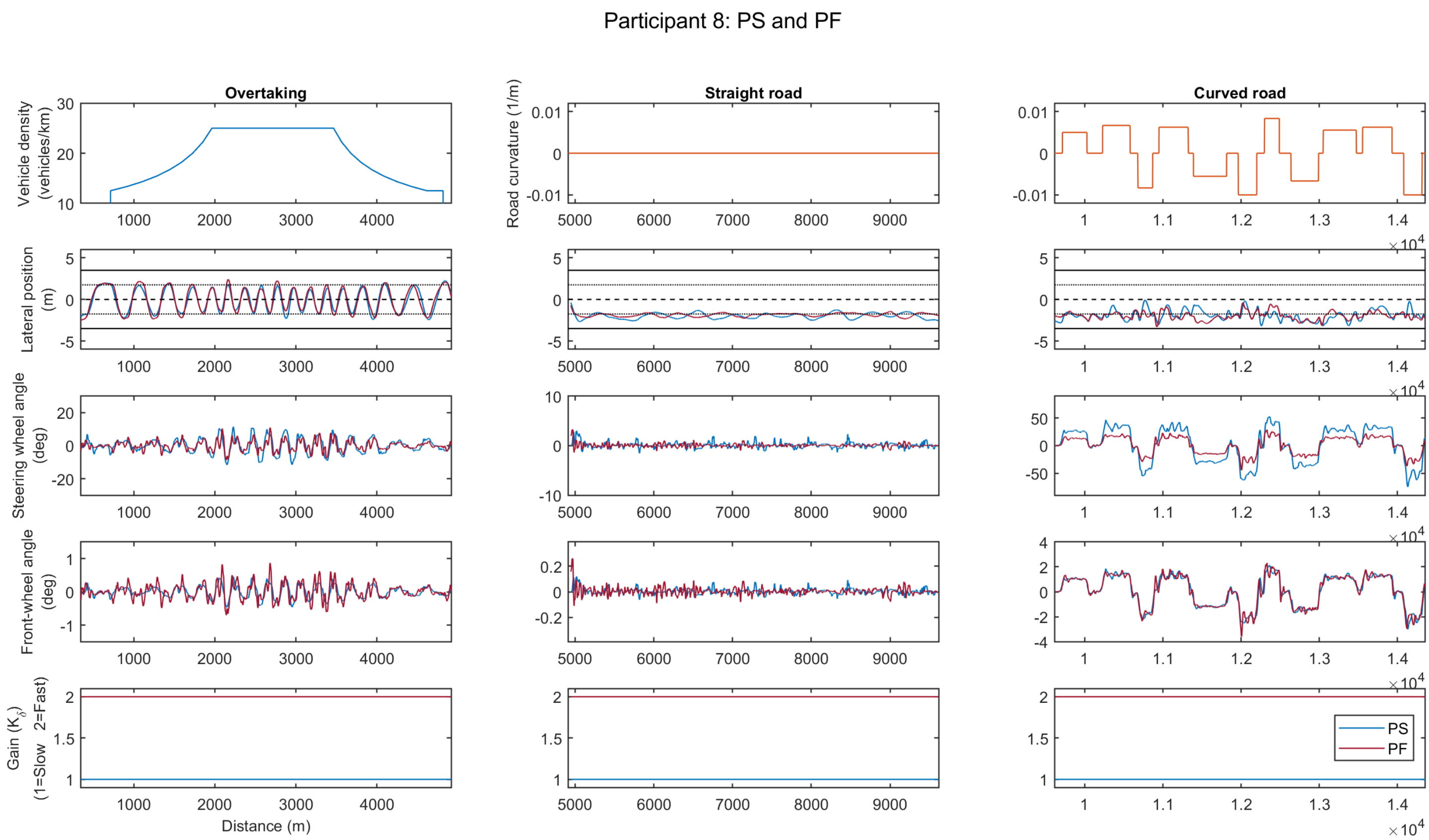


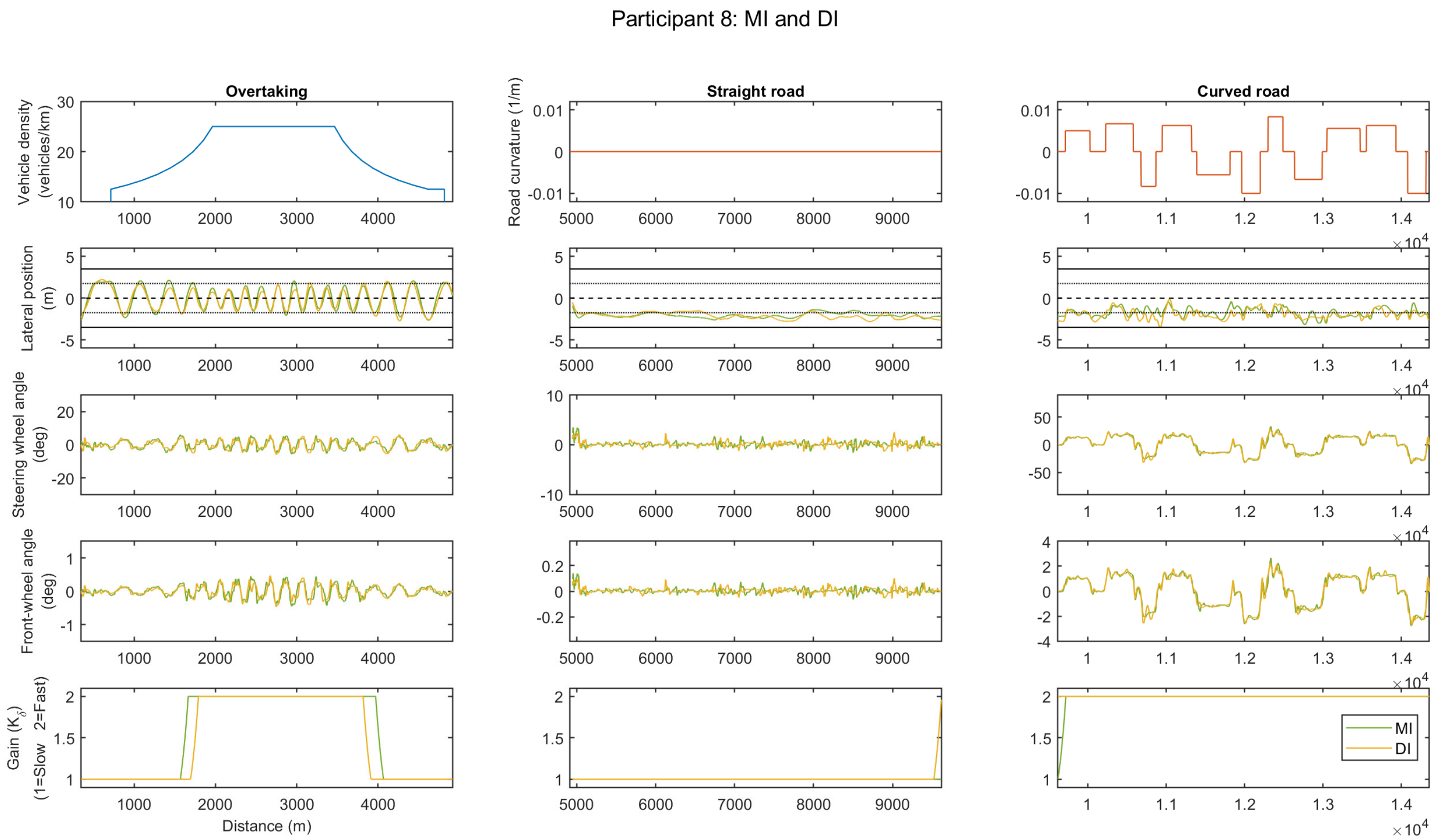
Participant 7: PS and PF



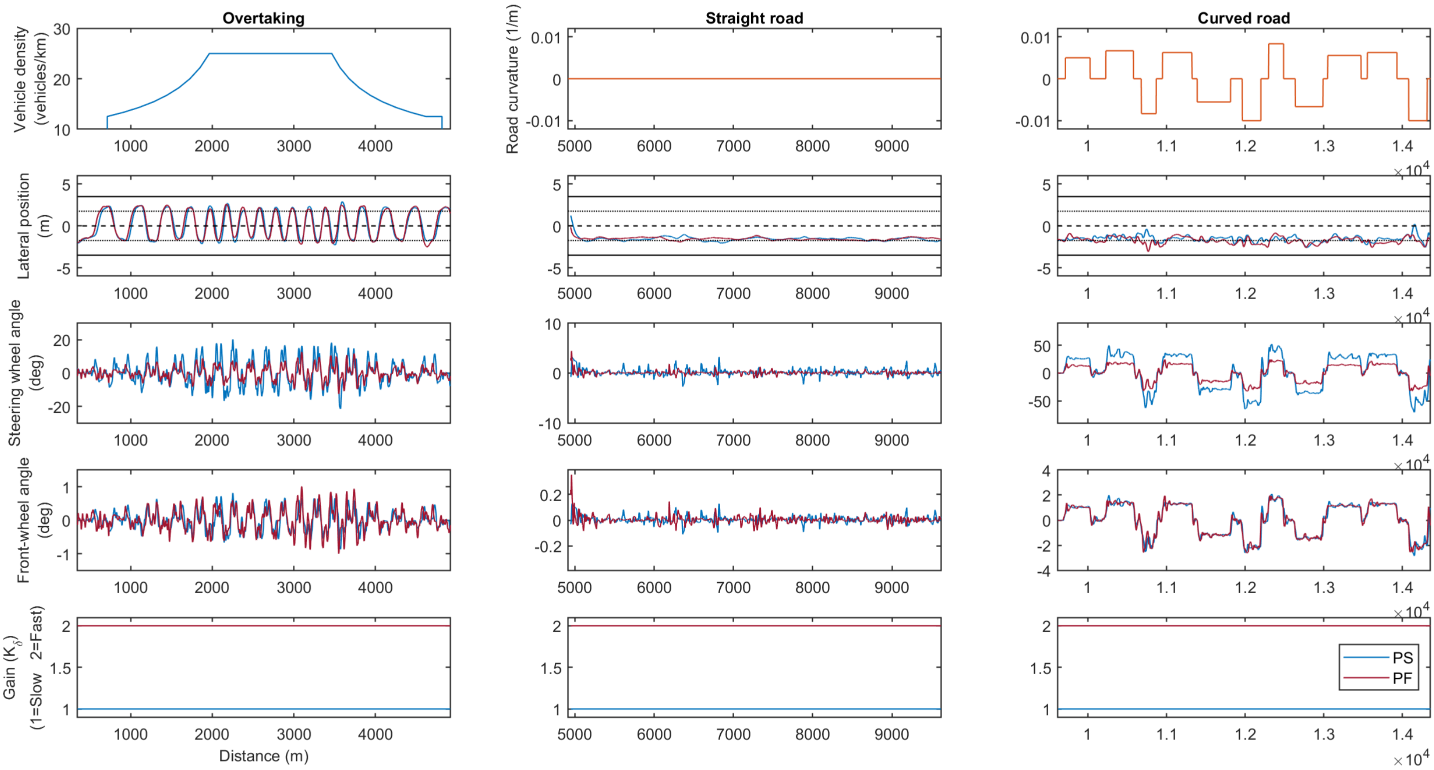
Participant 7: MI and DI



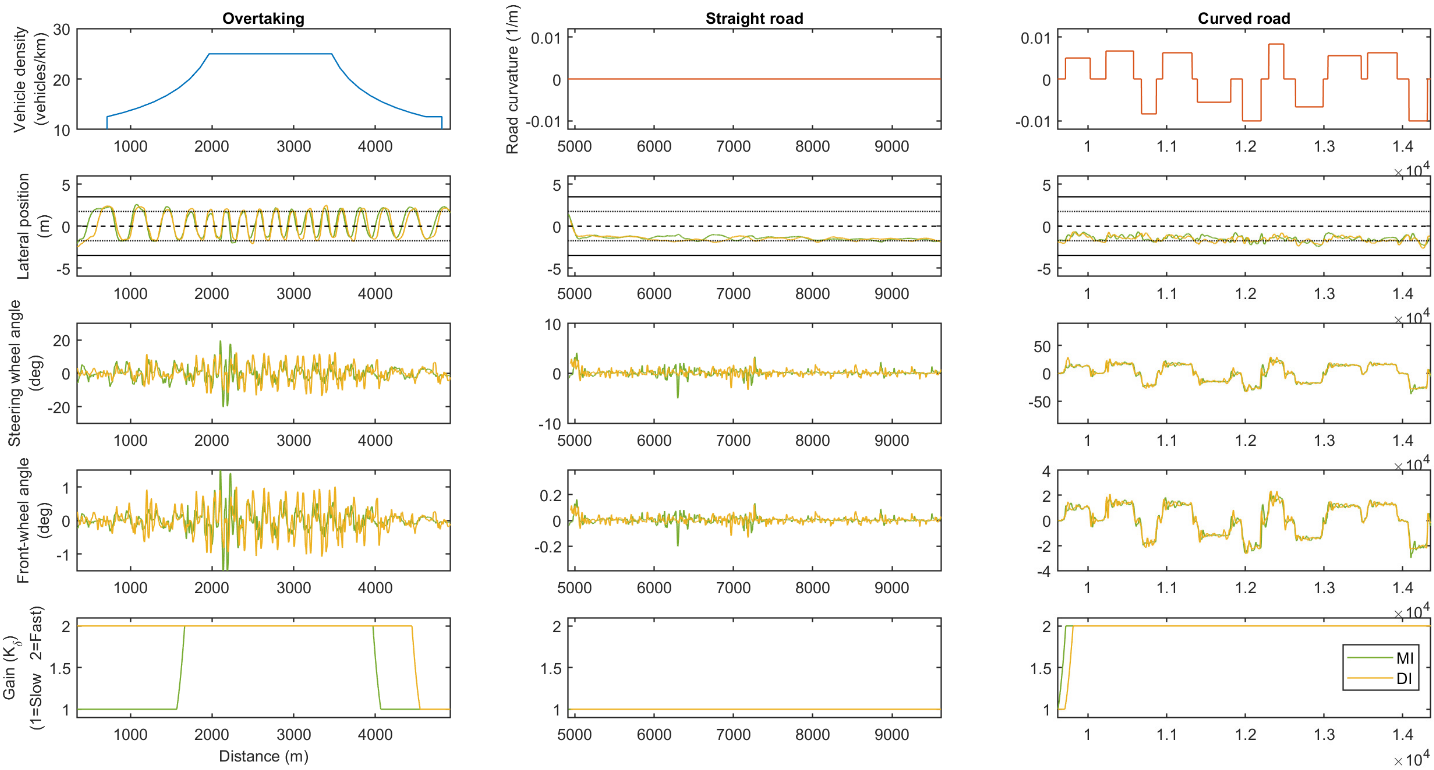

Participant 8: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF


Participant 8: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI

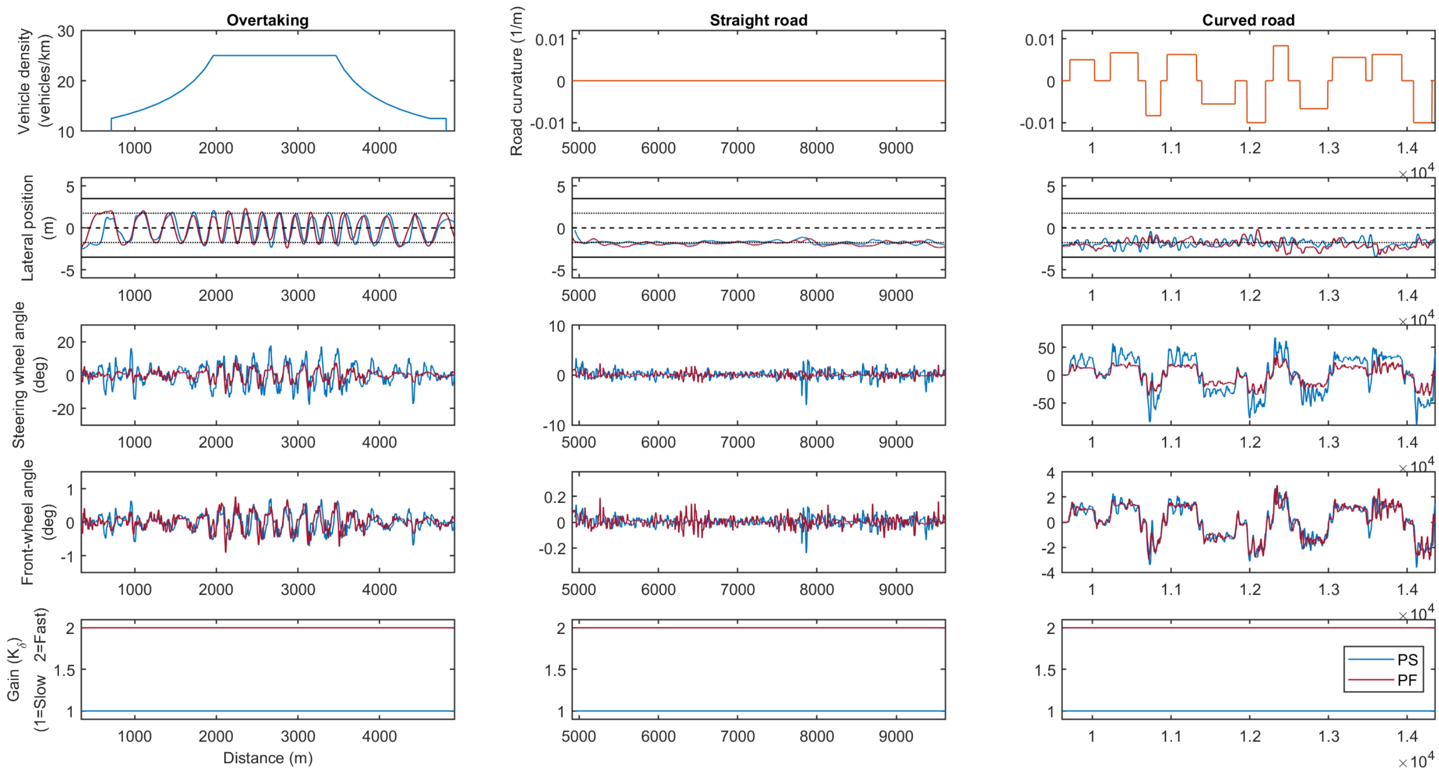
Participant 9: PS and PF



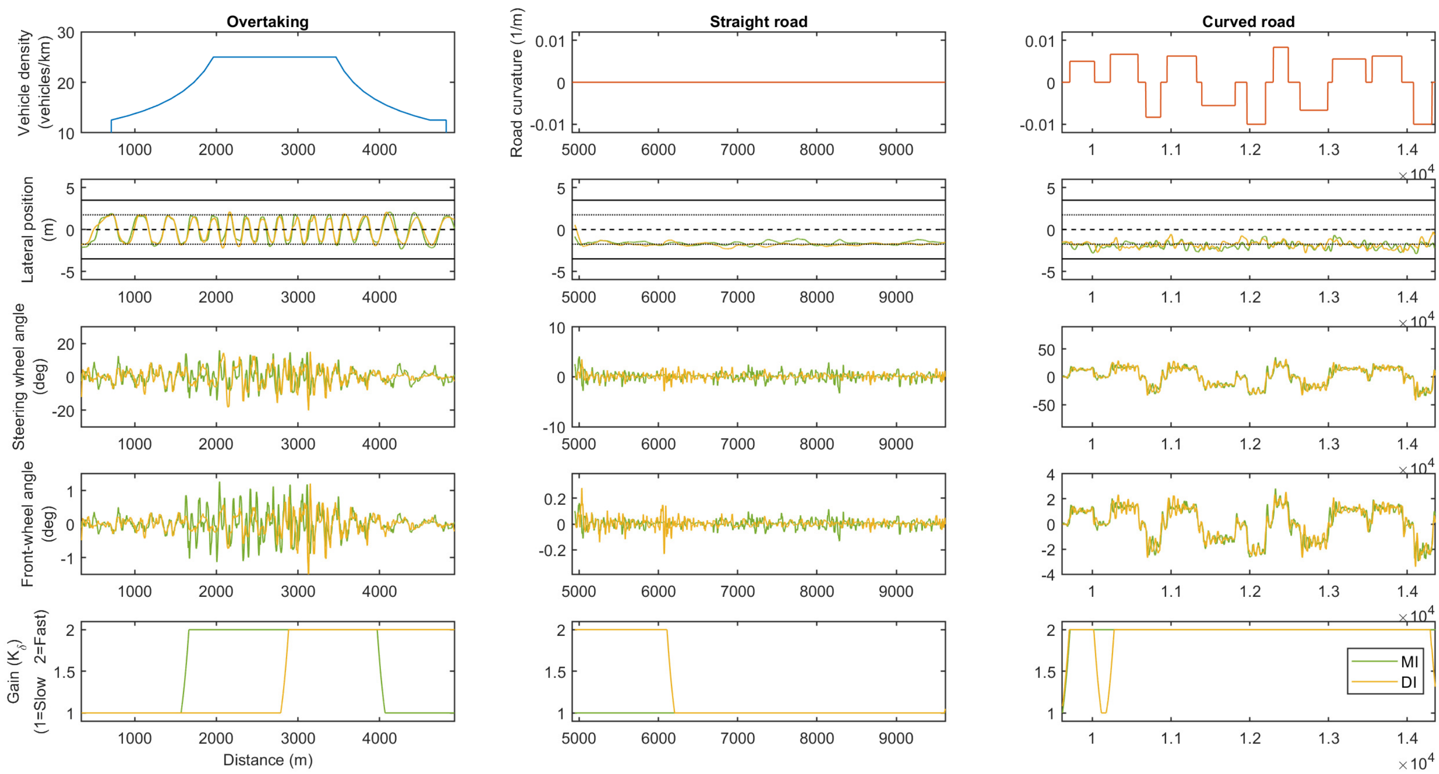
Participant 9: MI and DI

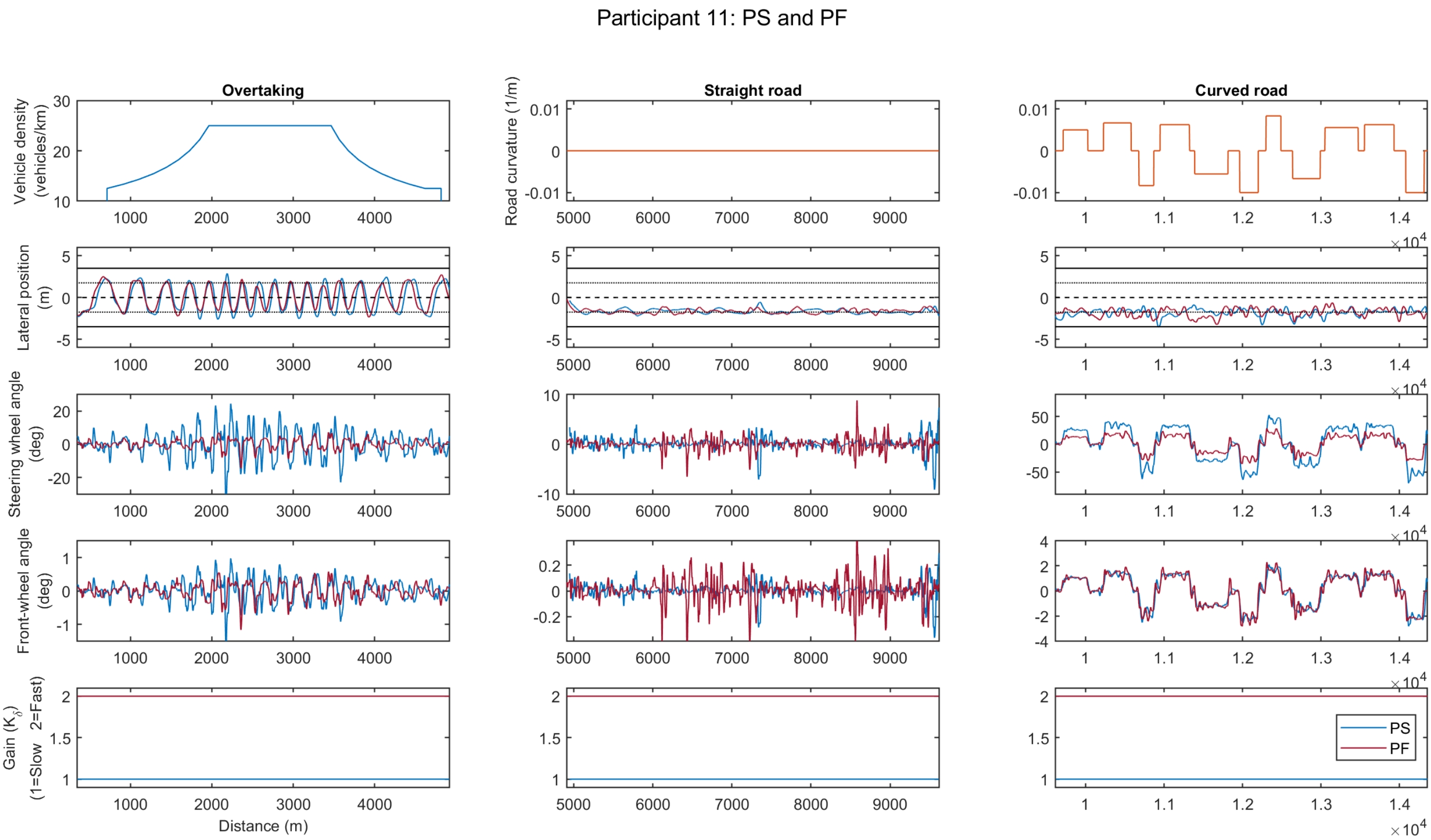


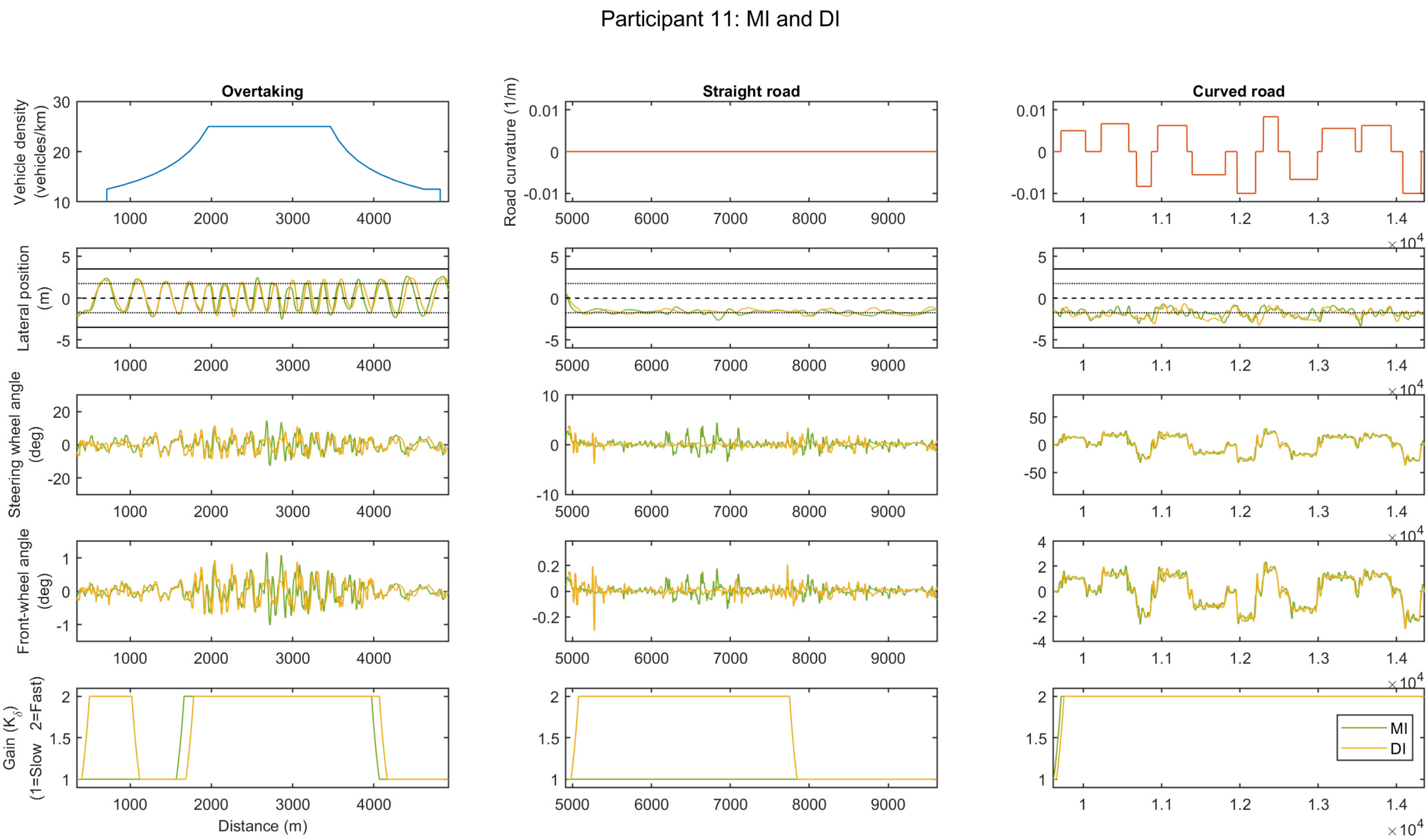
Participant 10: PS and PF



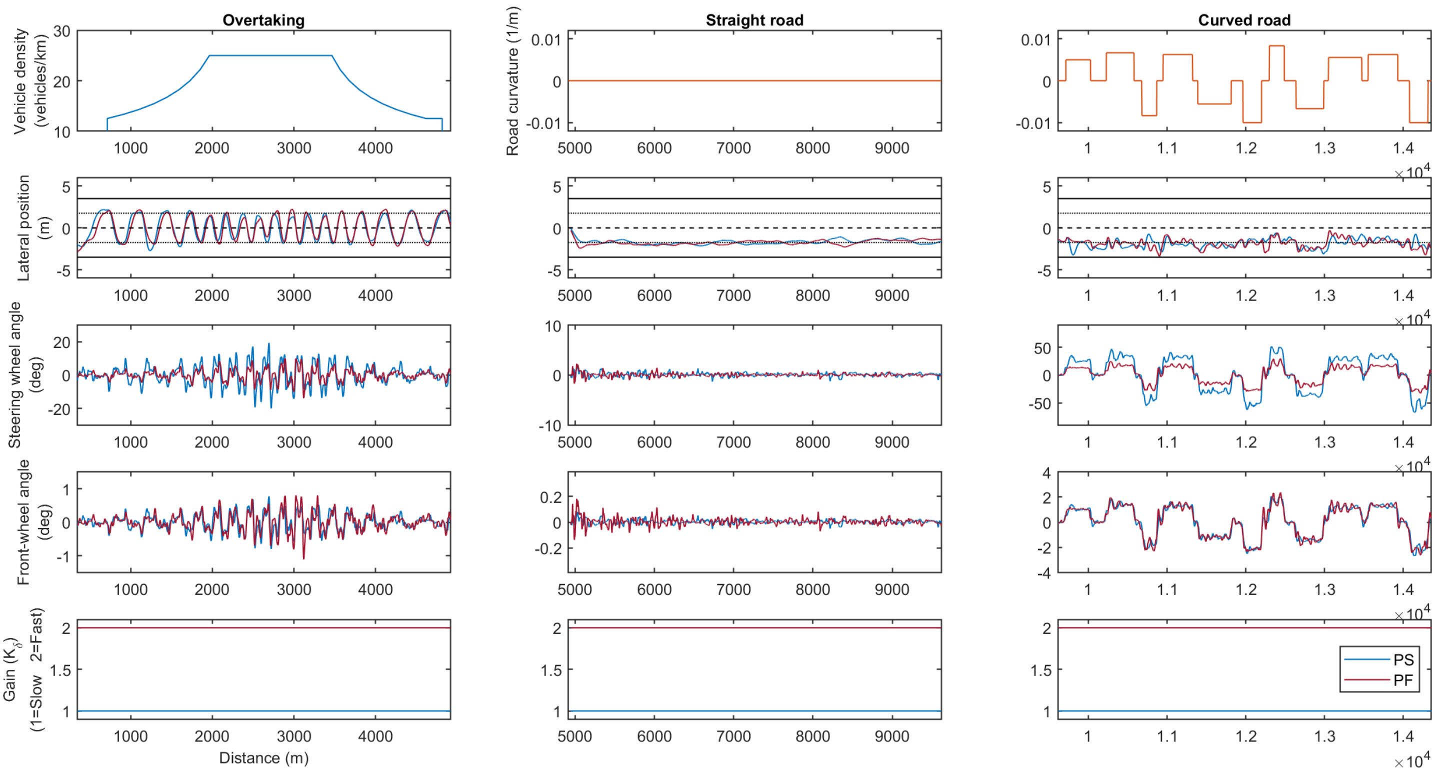
Participant 10: MI and DI



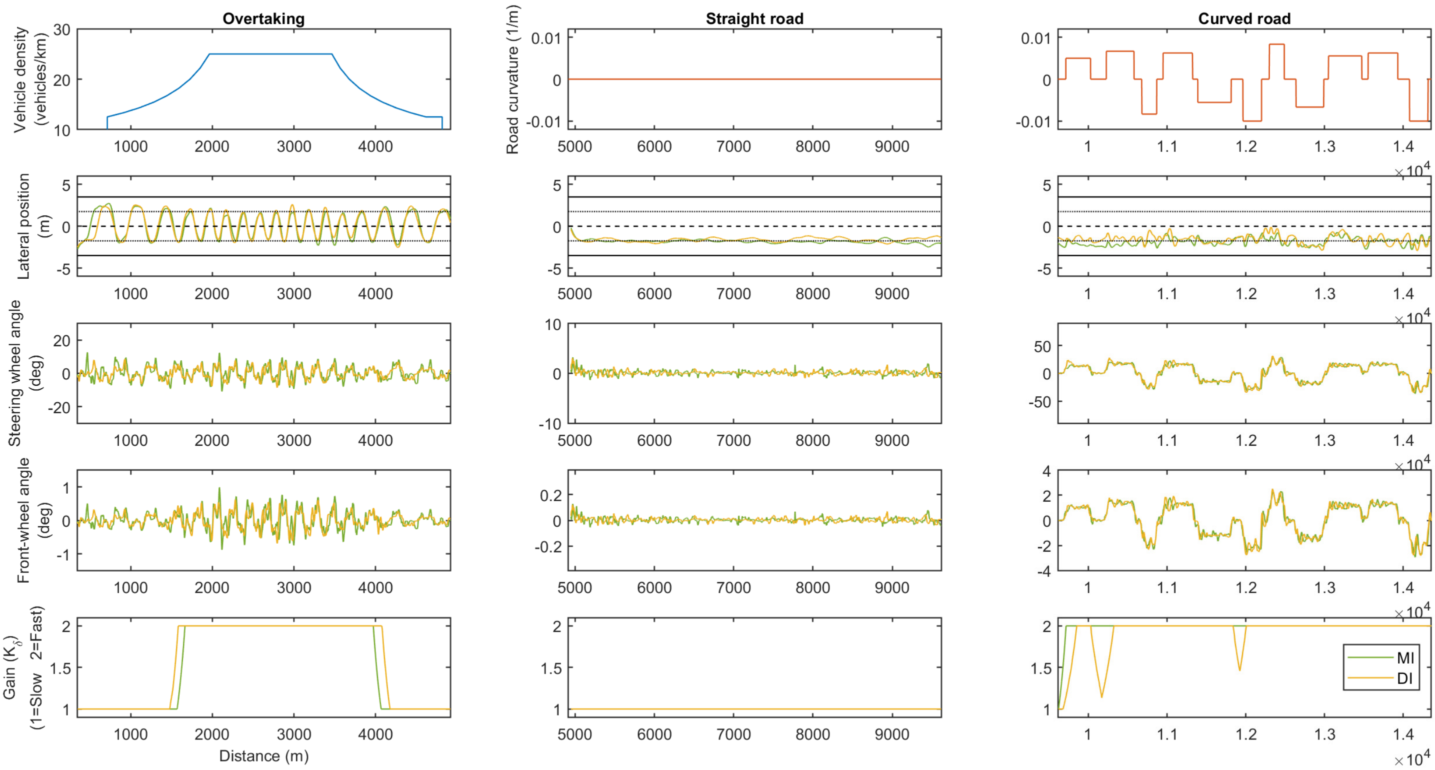

Participant 11: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF
$\times 10^4$

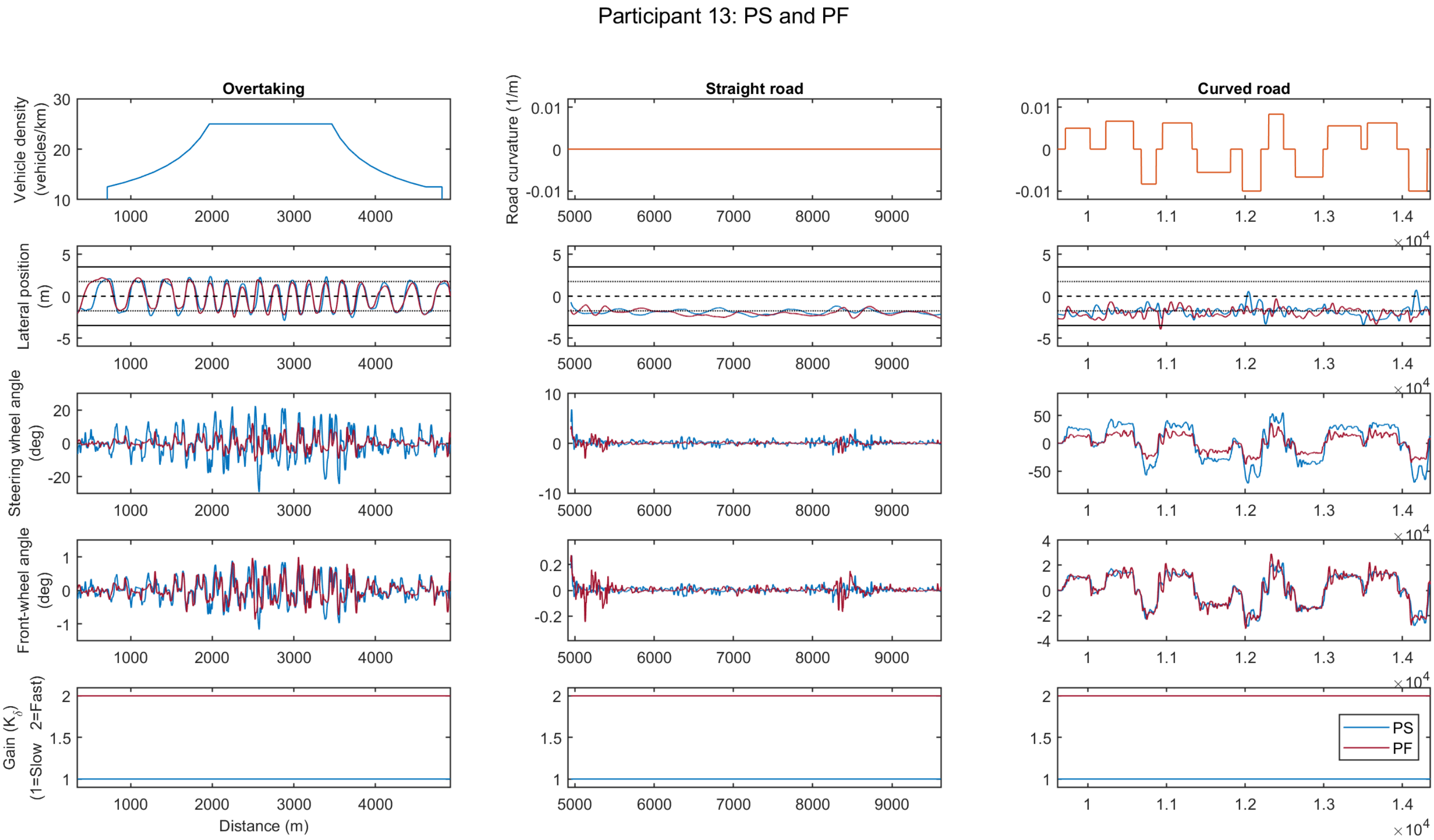

Participant 11: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI
$\times 10^4$

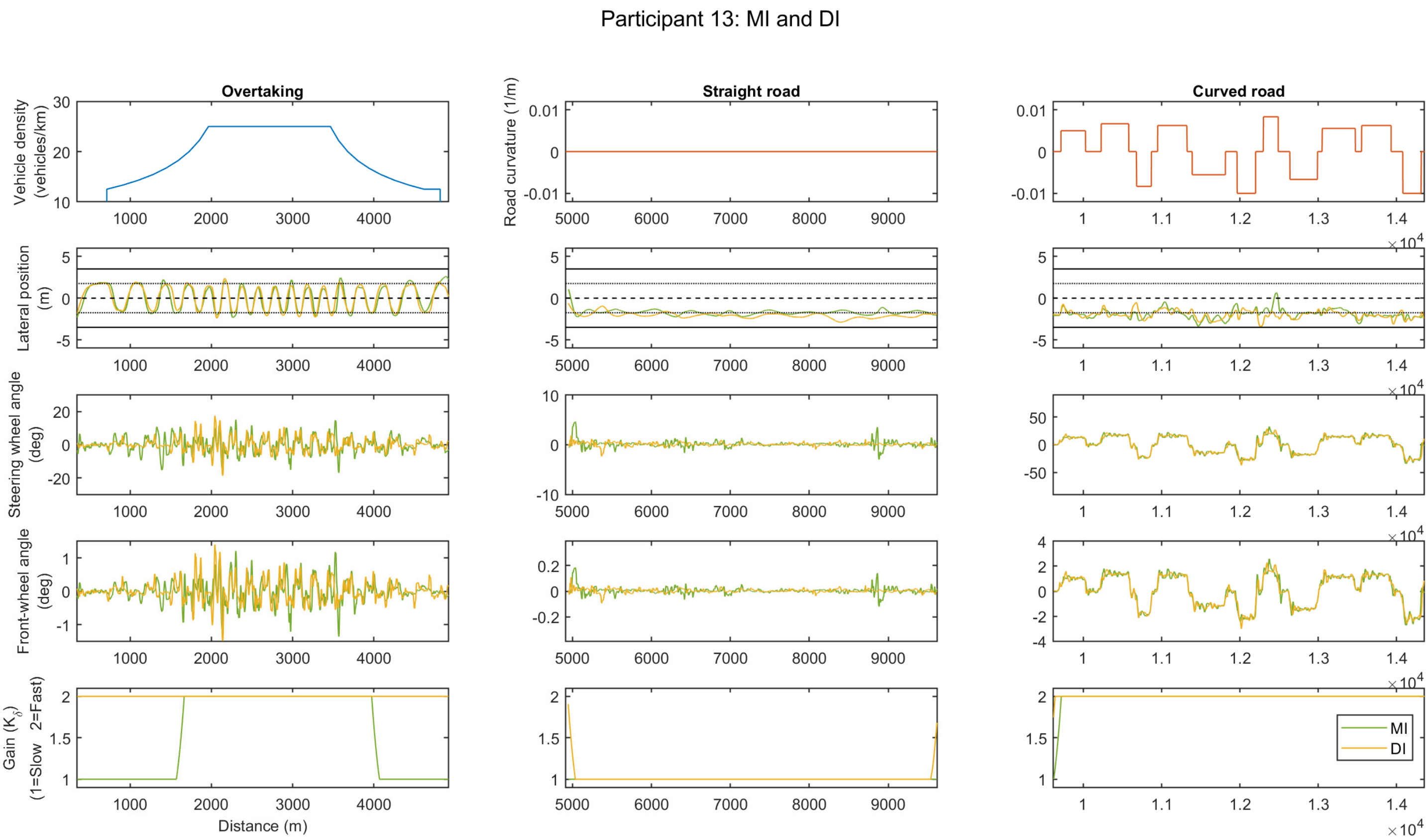
Participant 12: PS and PF



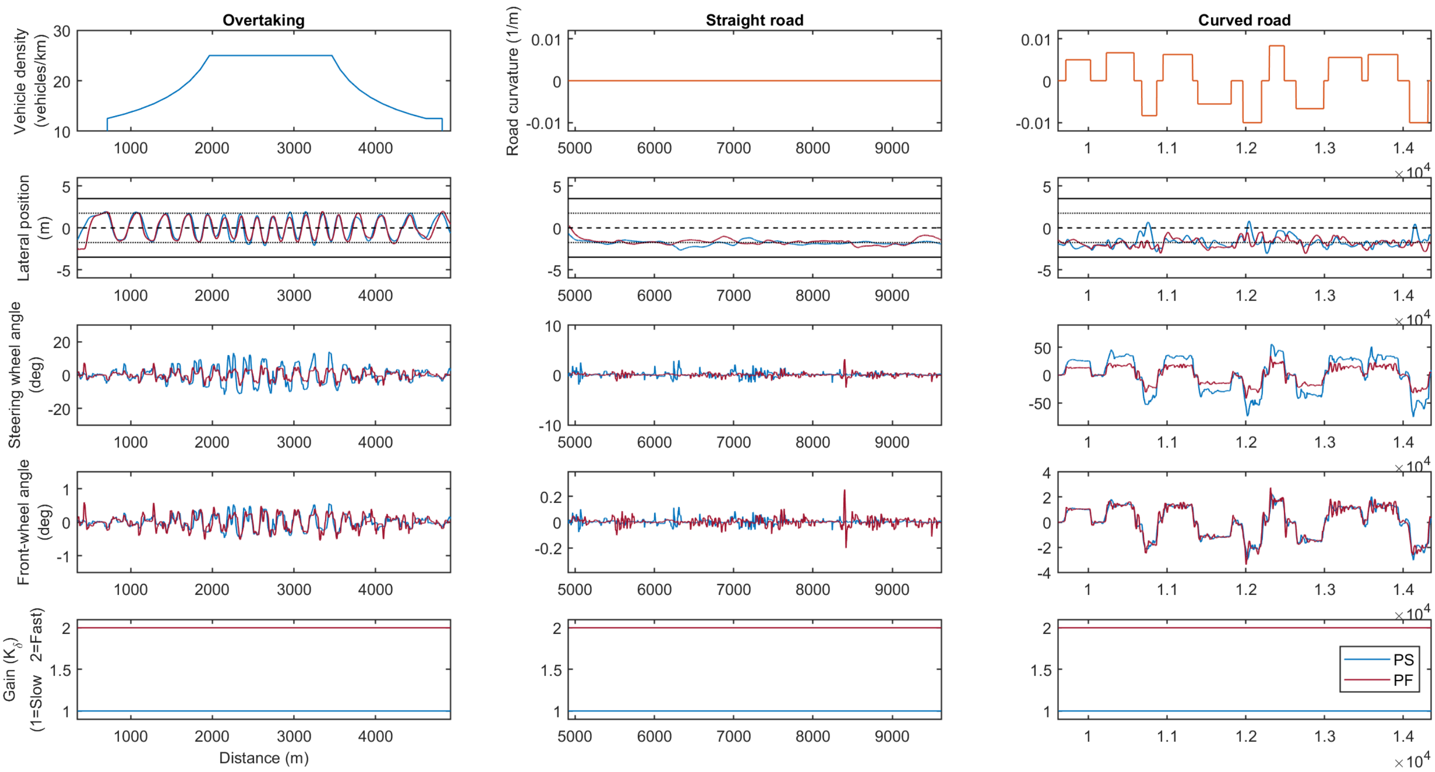
Participant 12: MI and DI



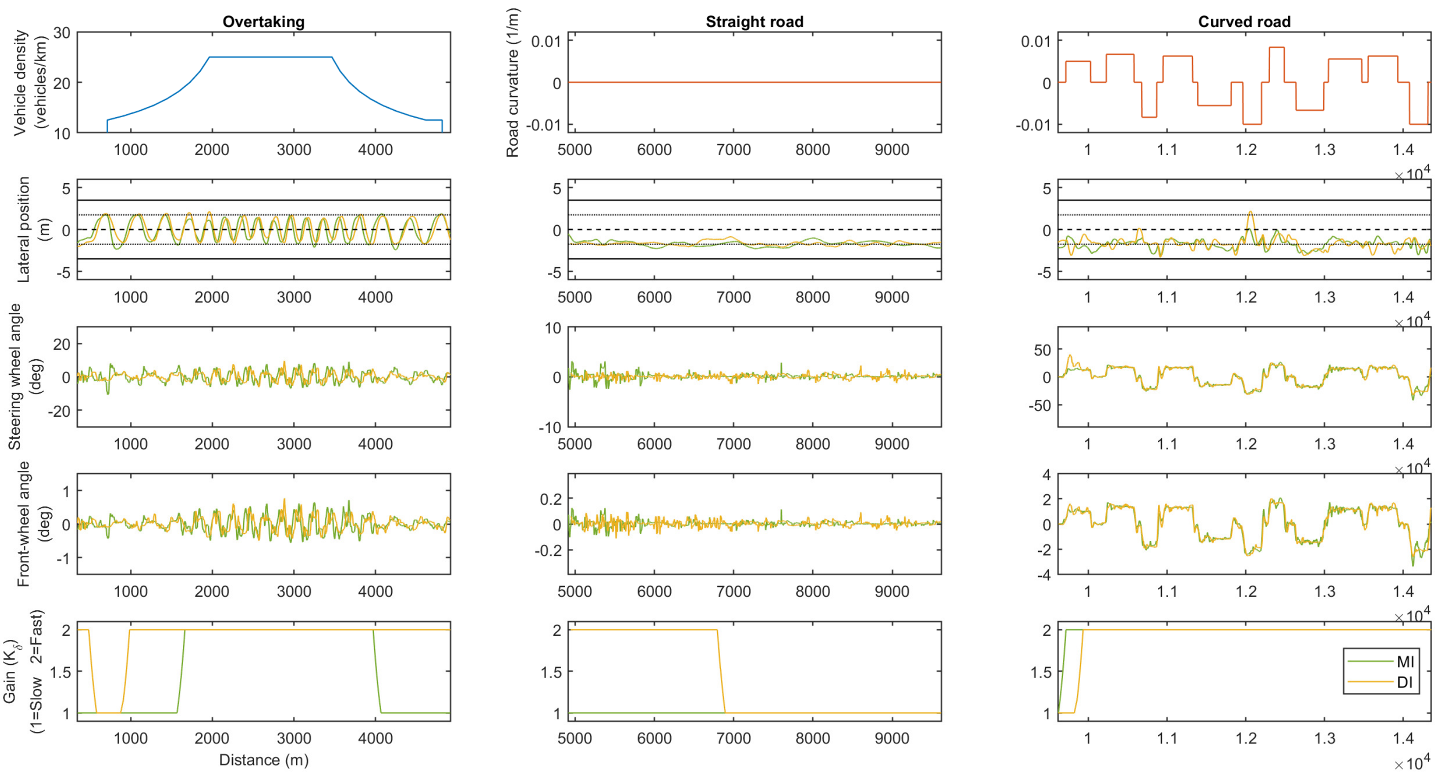

Participant 13: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF

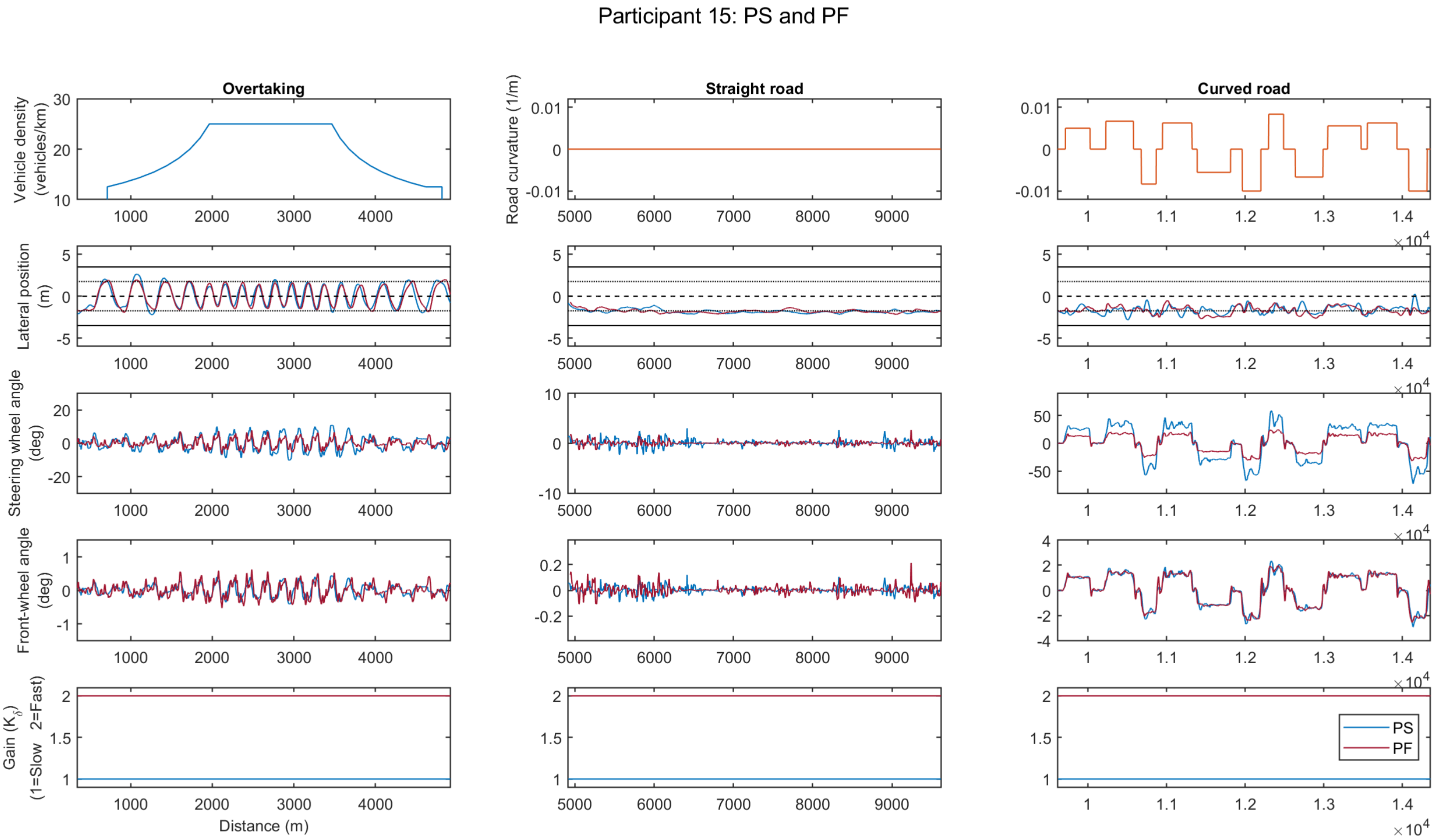

Participant 13: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI

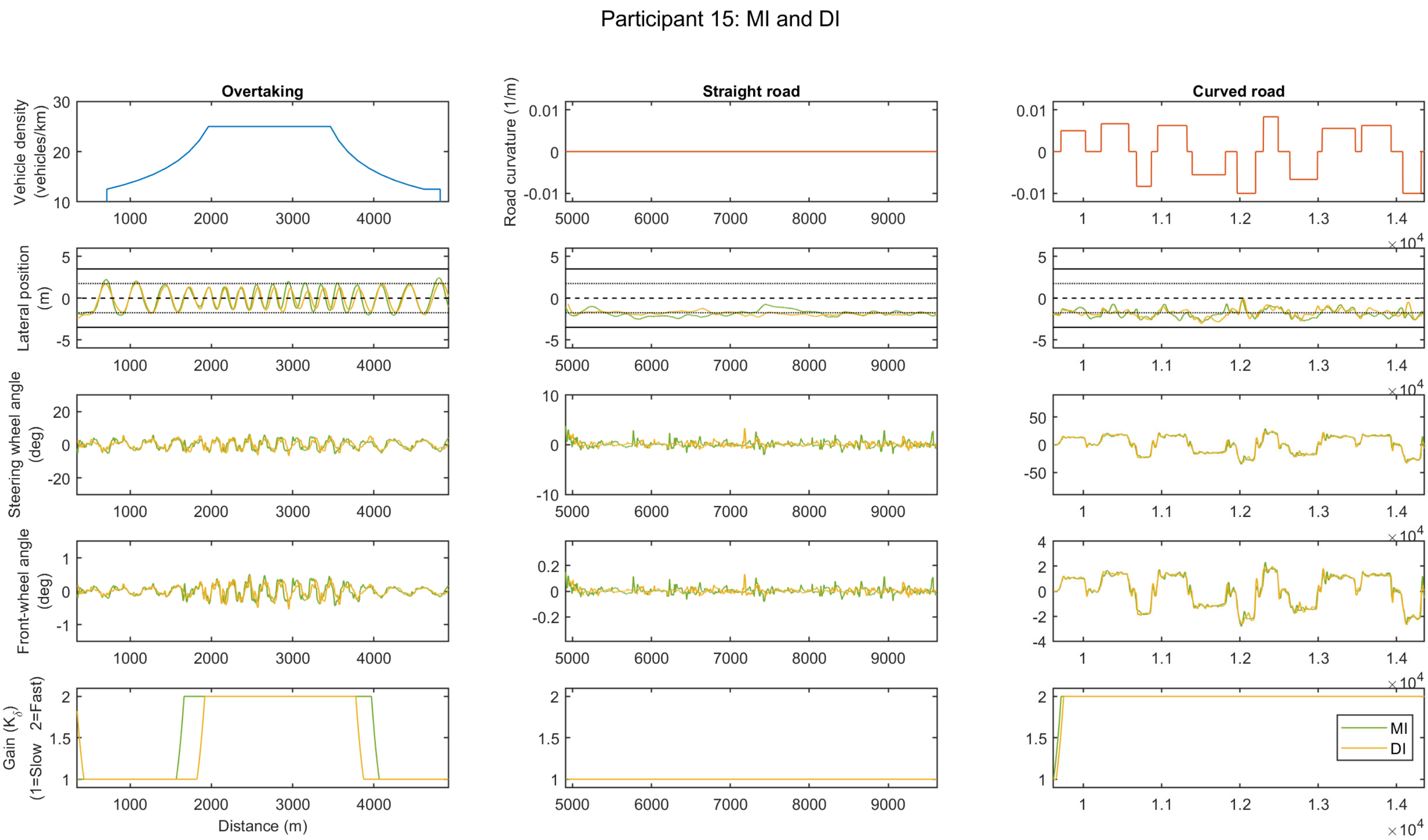
Participant 14: PS and PF



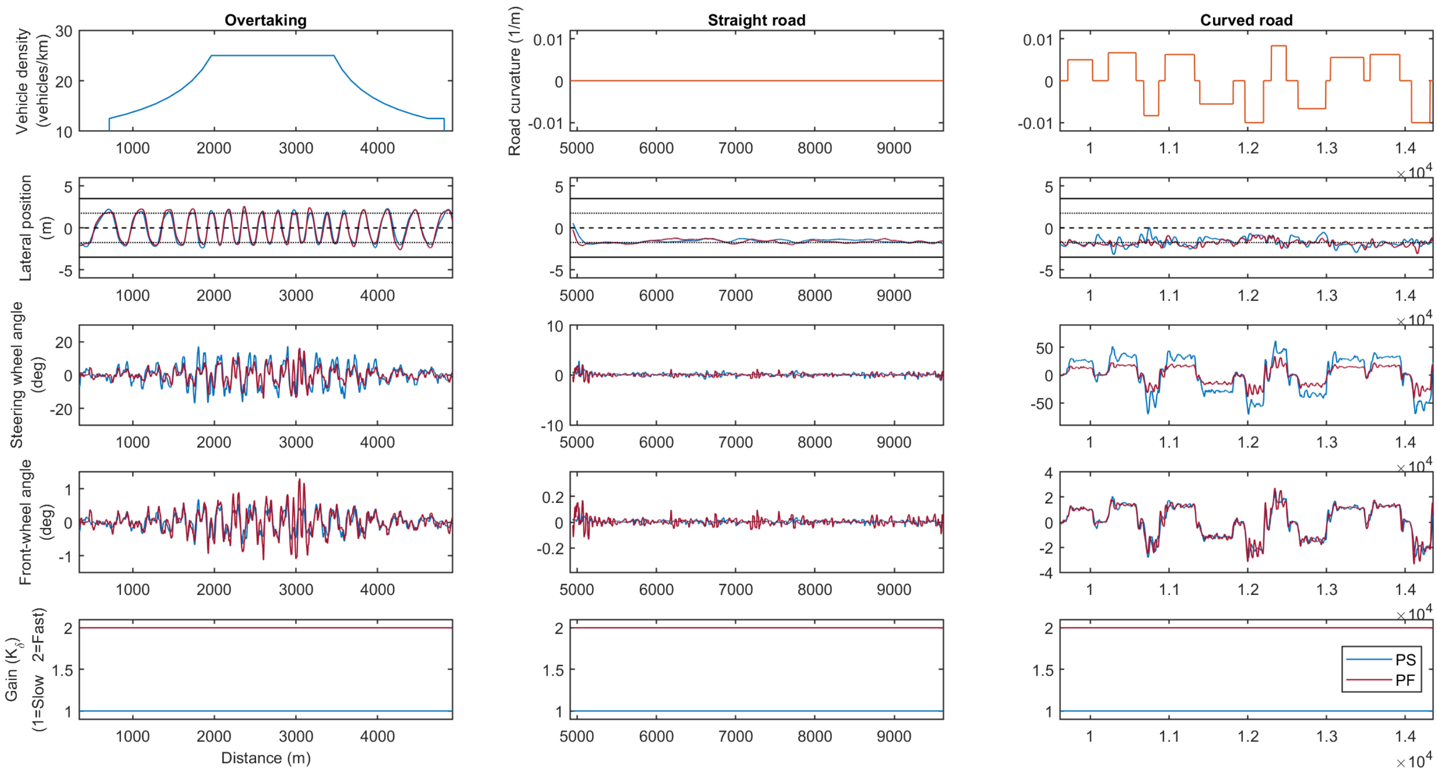
Participant 14: MI and DI



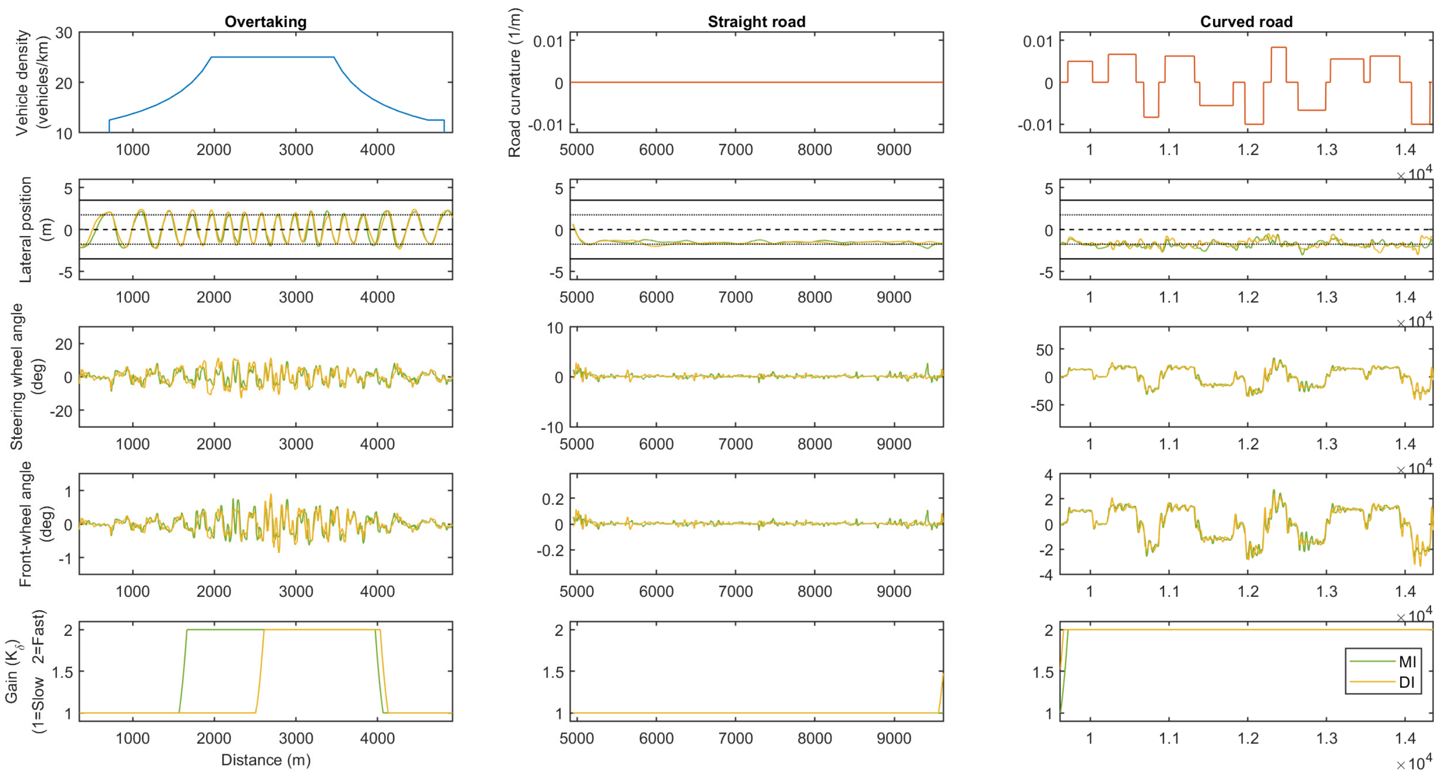

Participant 15: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF


Participant 15: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI

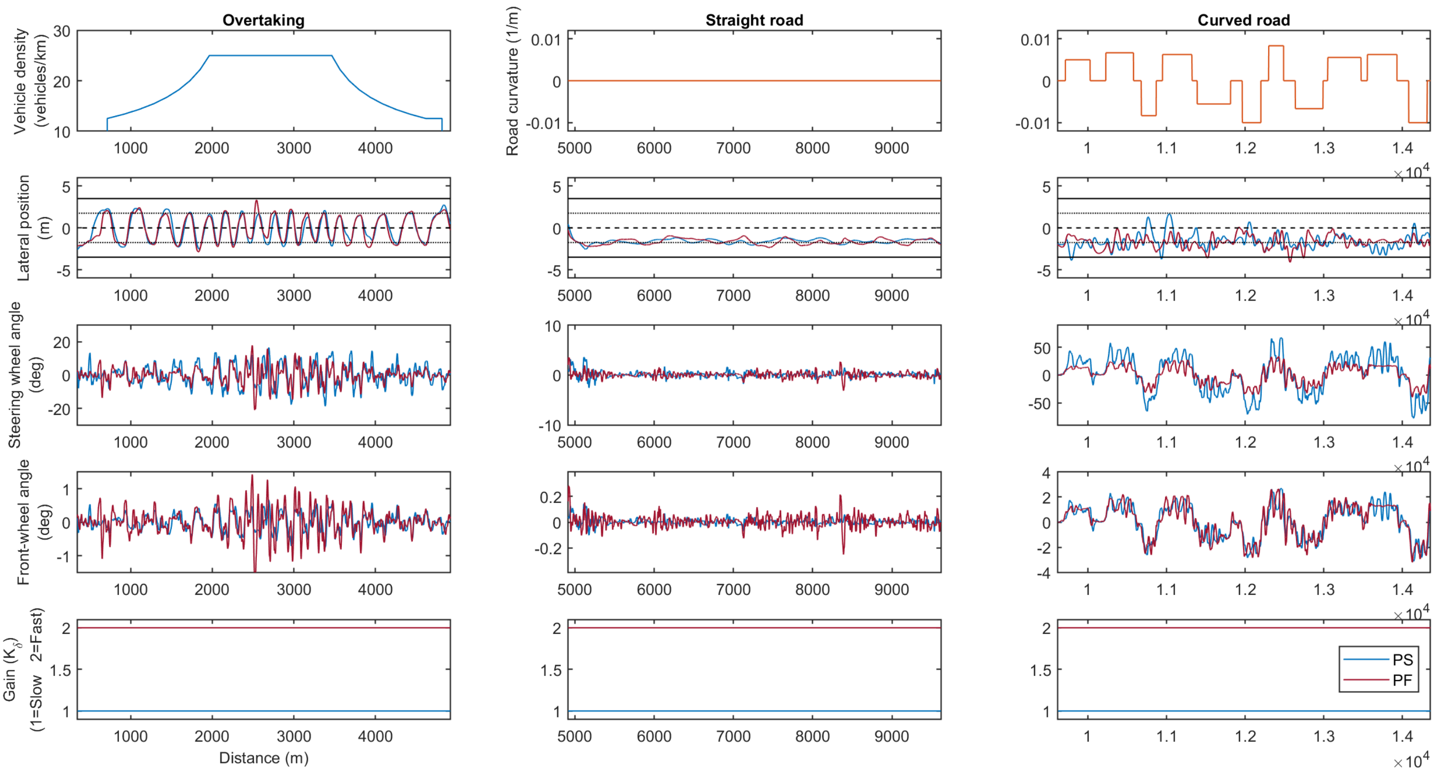
Participant 16: PS and PF



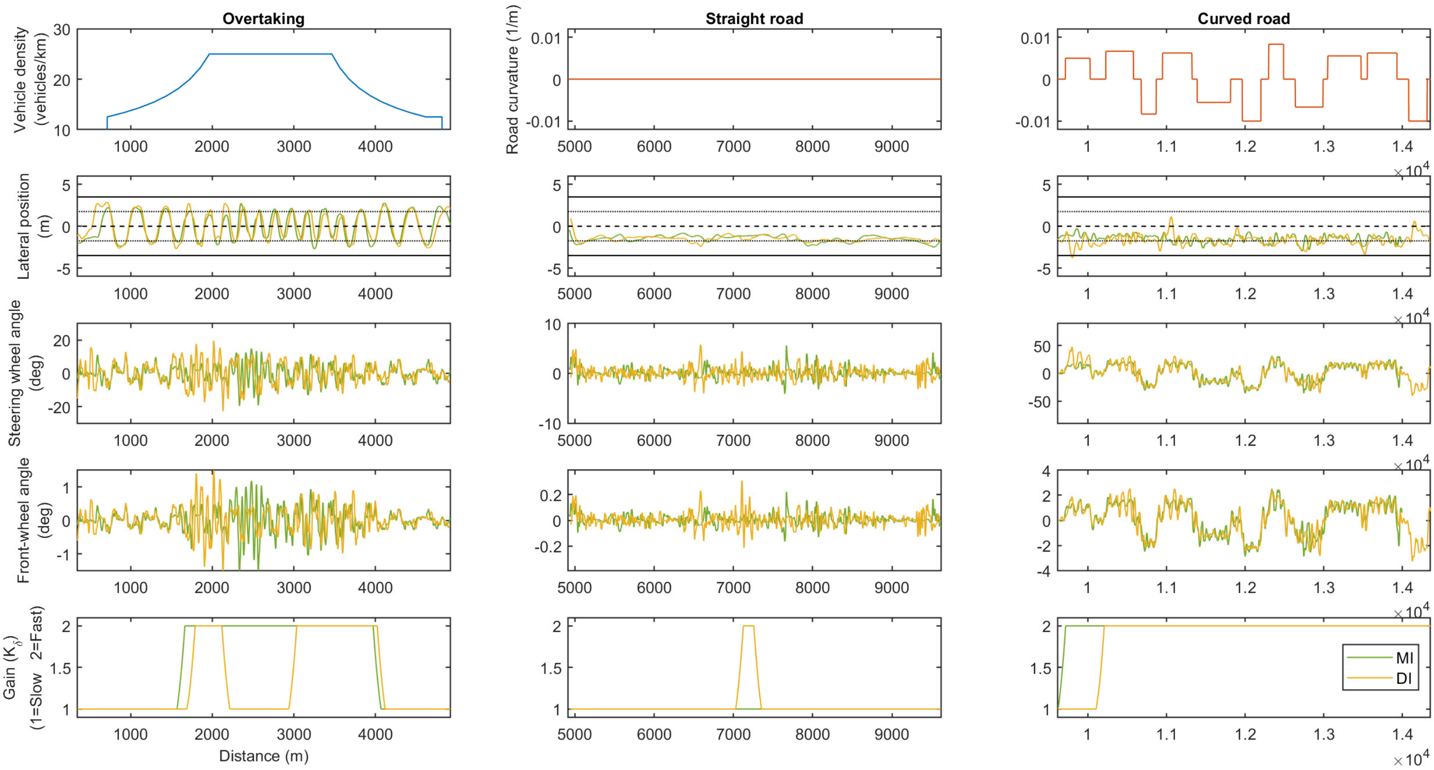
Participant 16: MI and DI

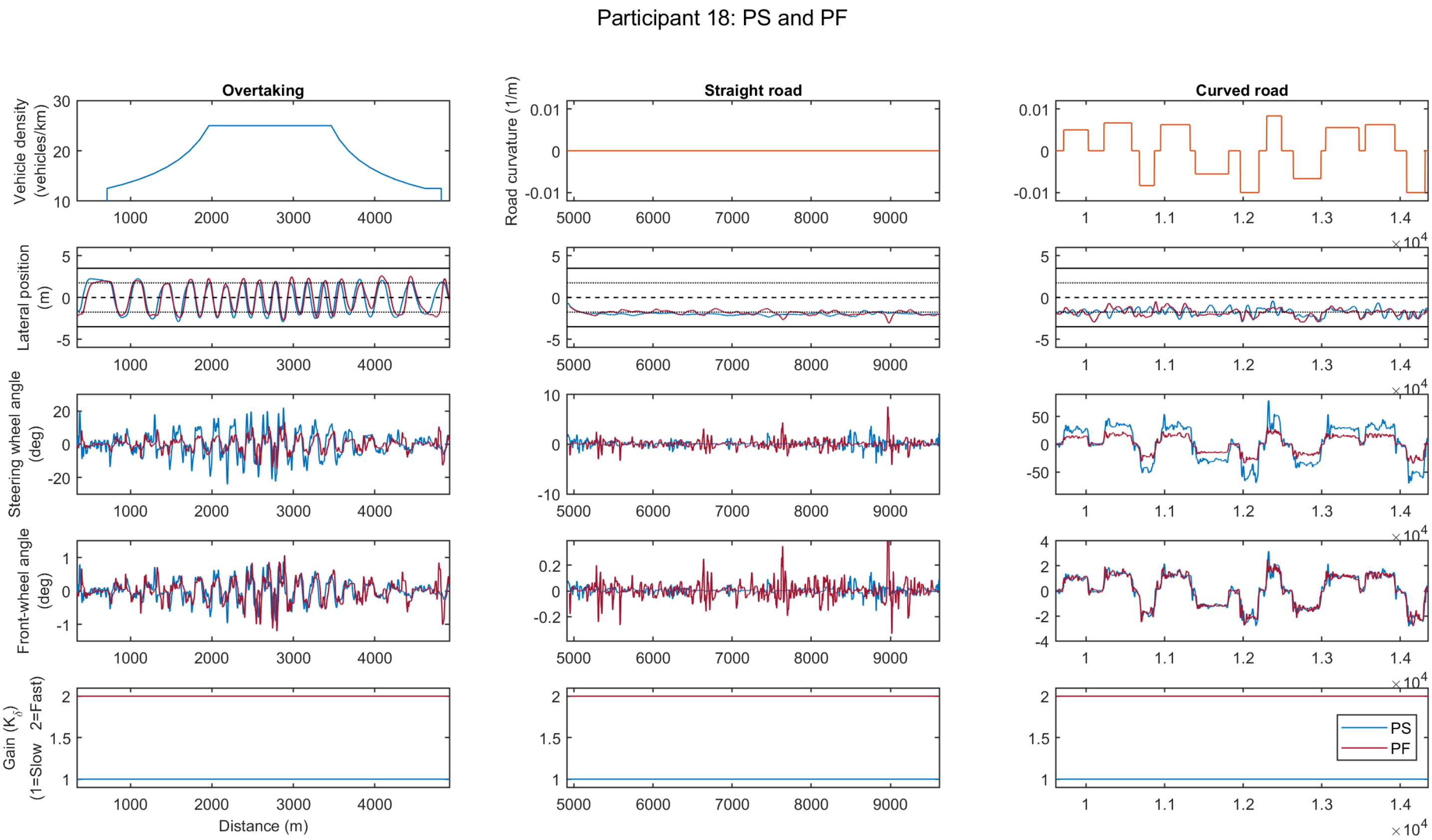


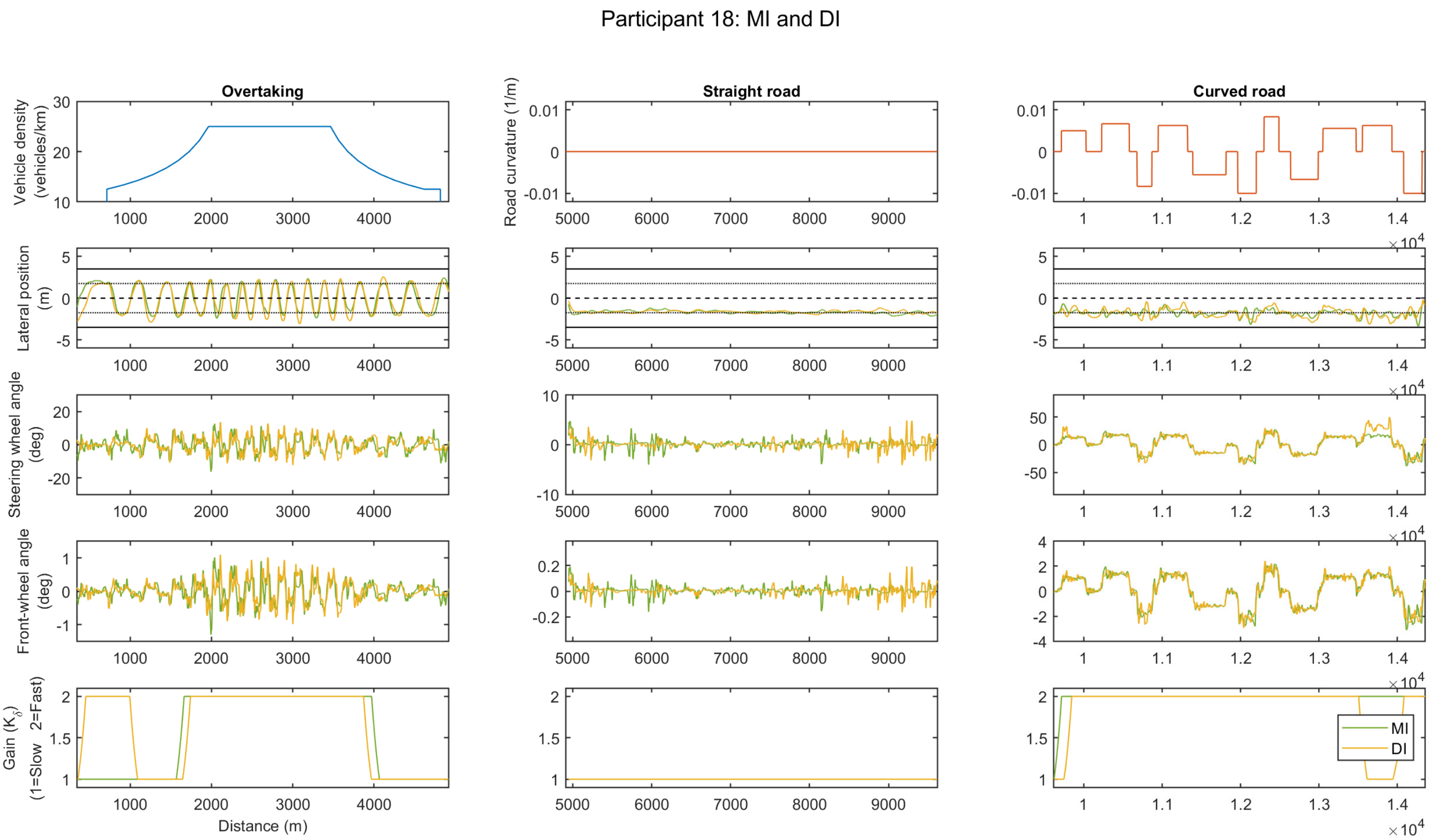
Participant 17: PS and PF

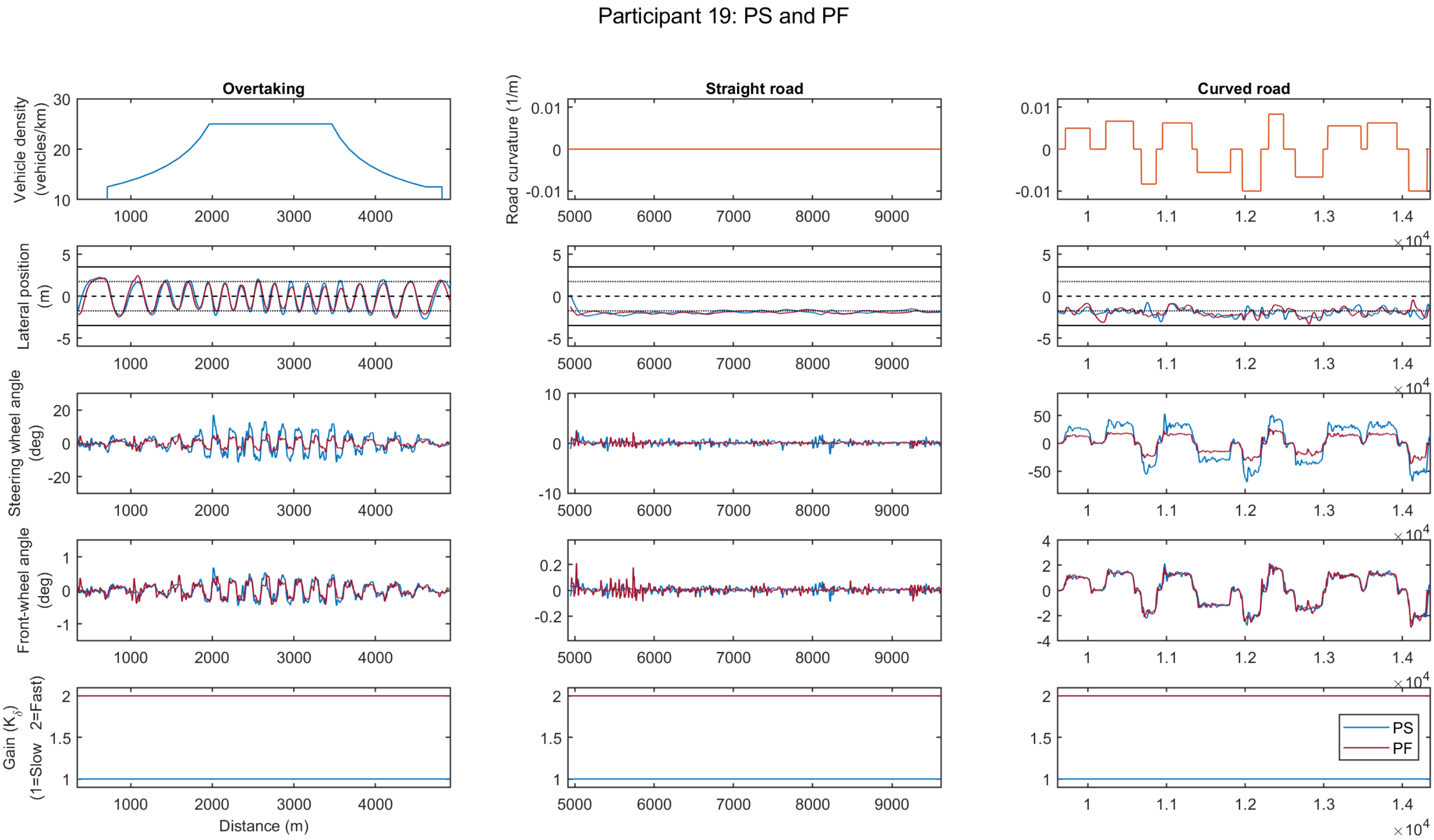


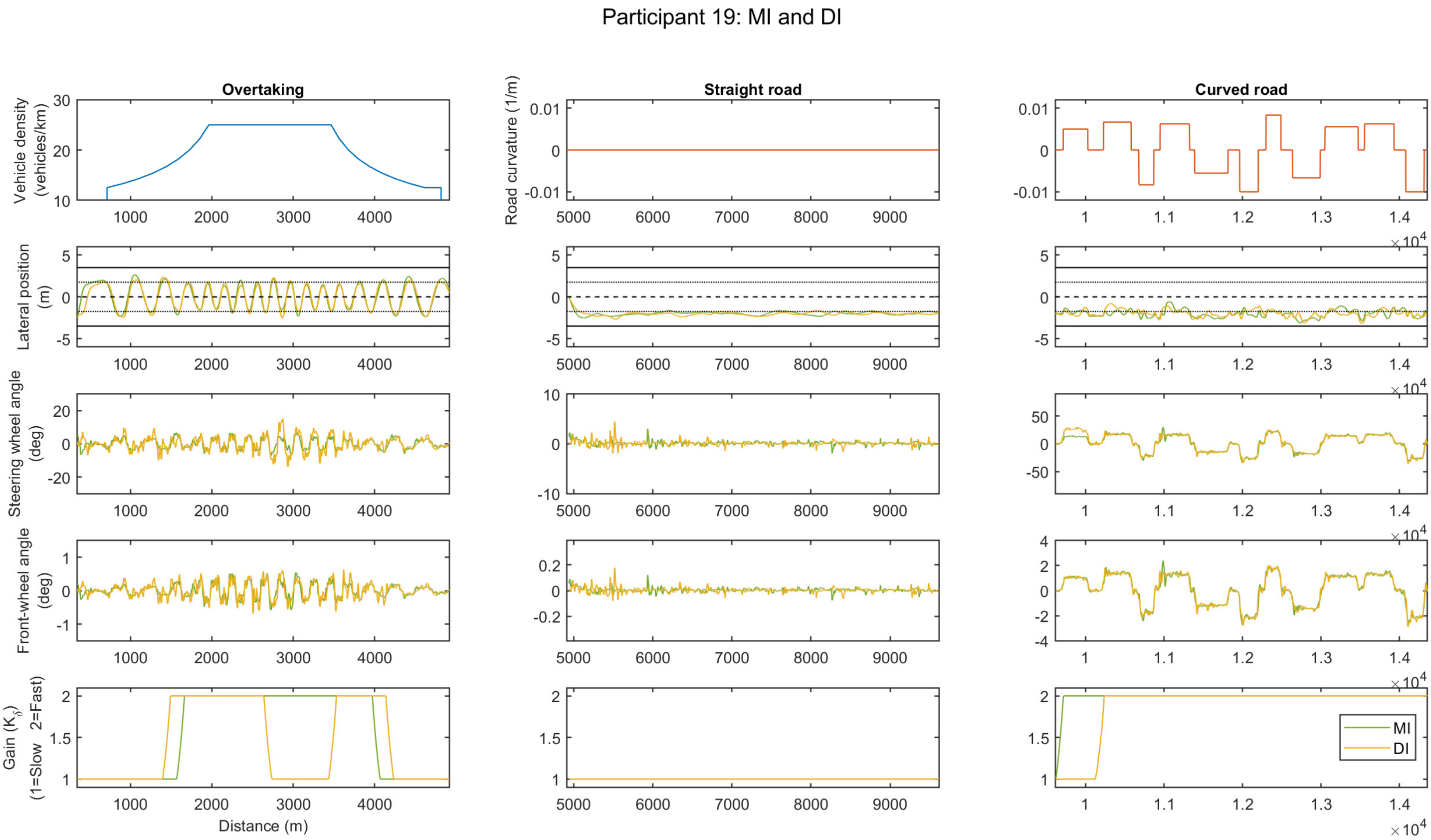
Participant 17: MI and DI



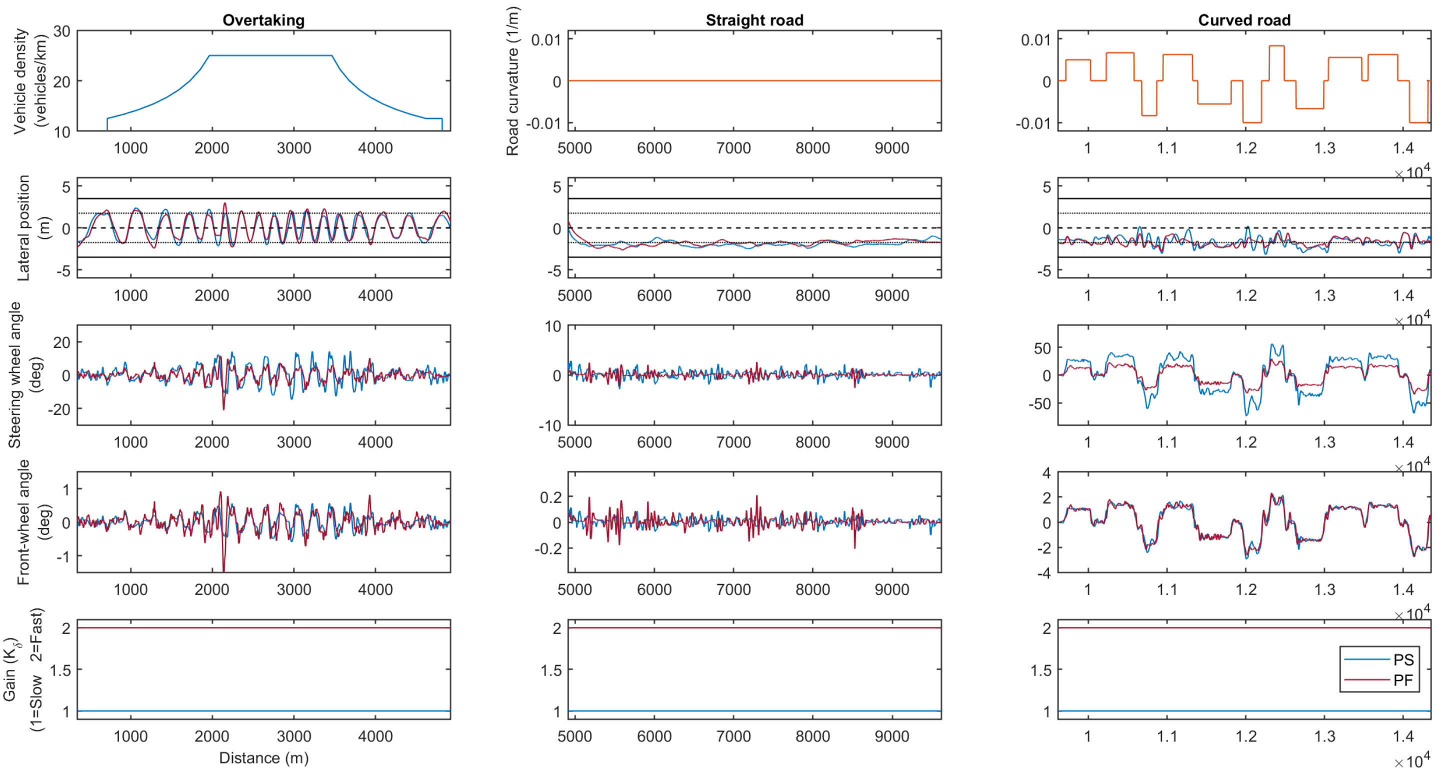

Participant 18: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
$\times 10^4$
PS
PF


Participant 18: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
$\times 10^4$
MI
DI

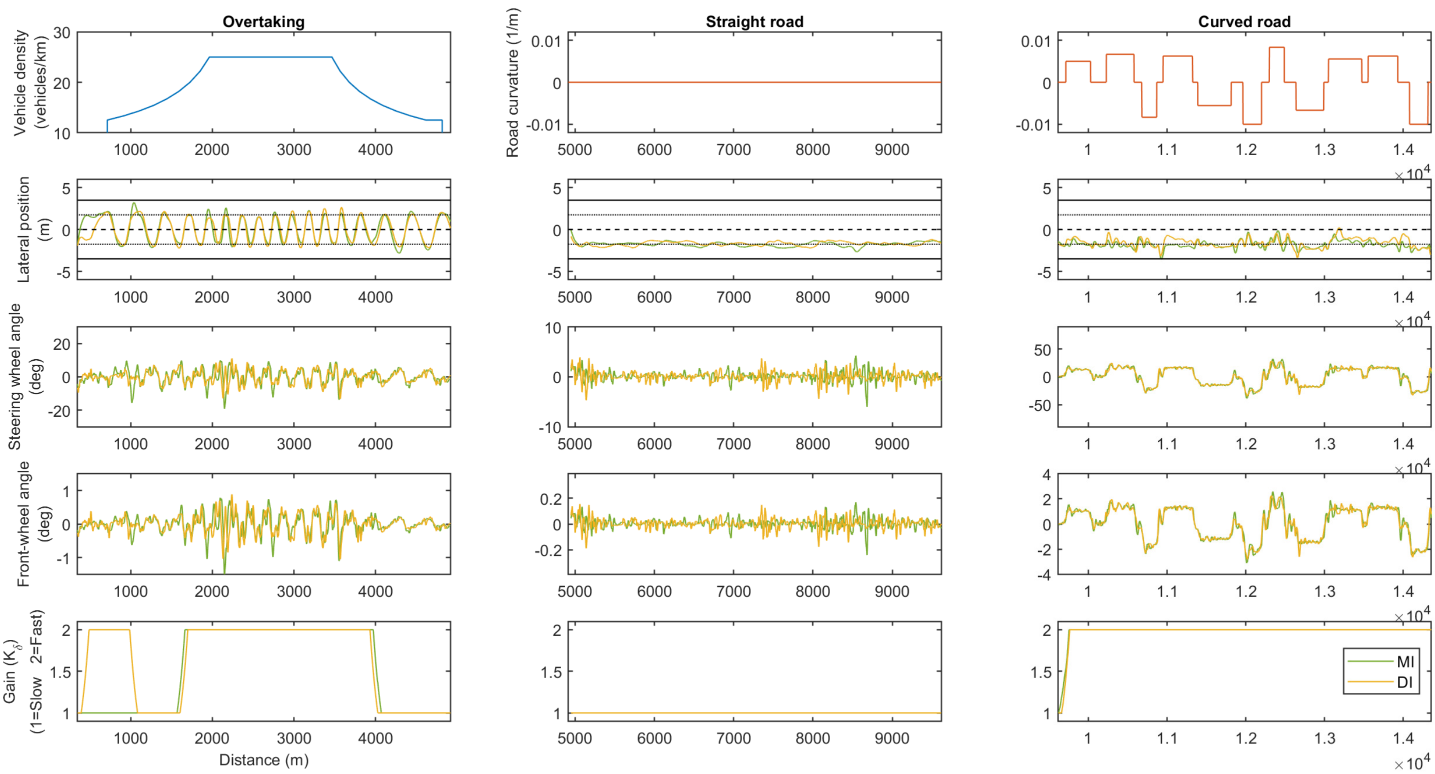

Participant 19: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF
×10^4


Participant 19: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI
×10^4

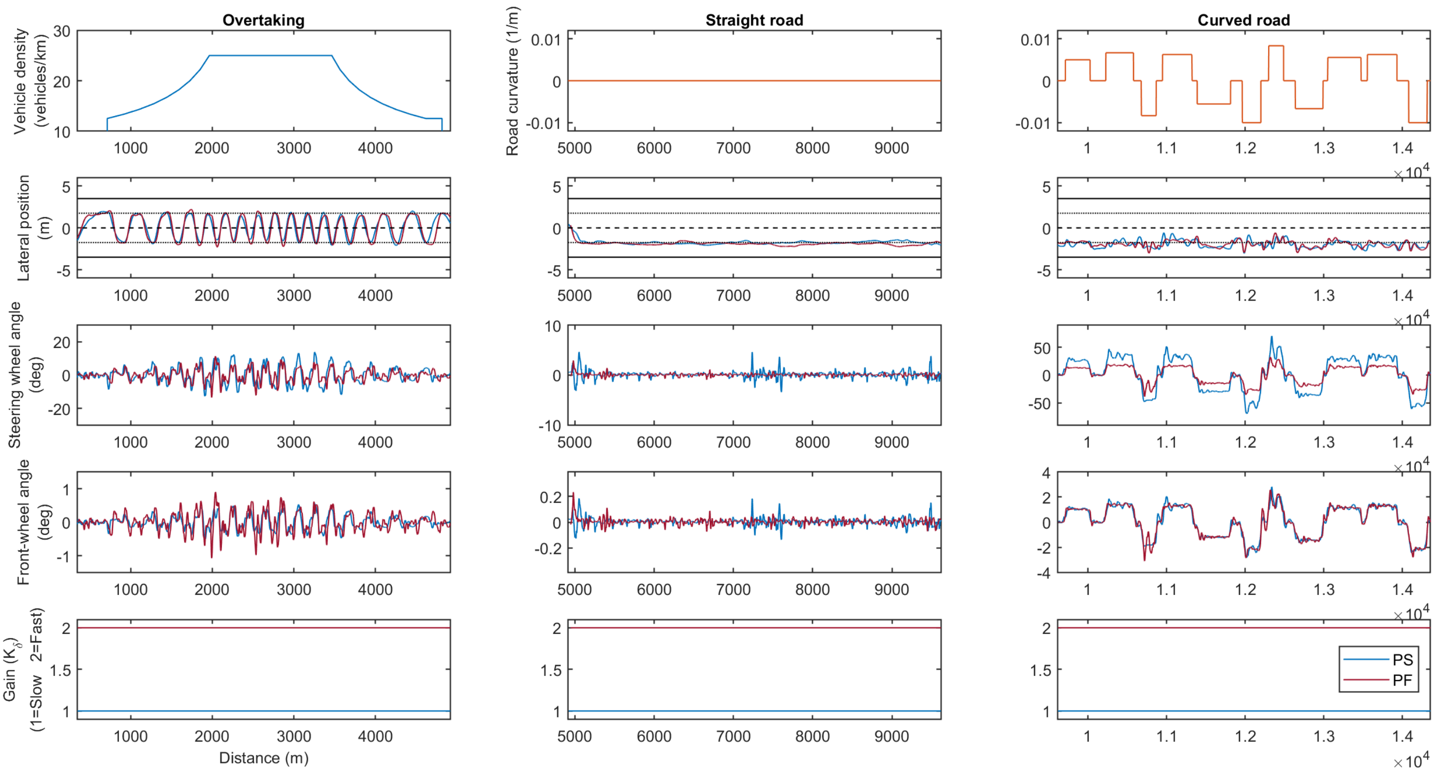
Participant 20: PS and PF



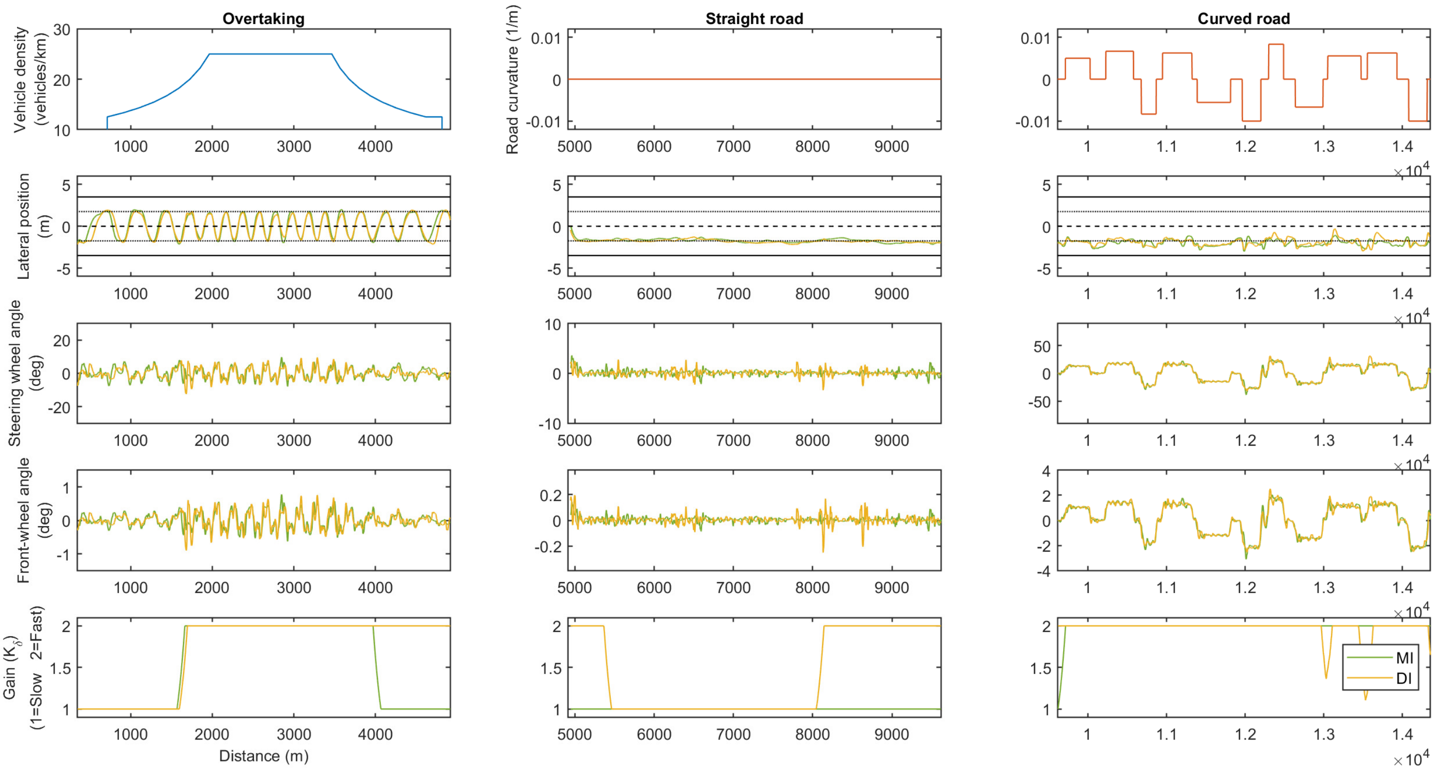
Participant 20: MI and DI

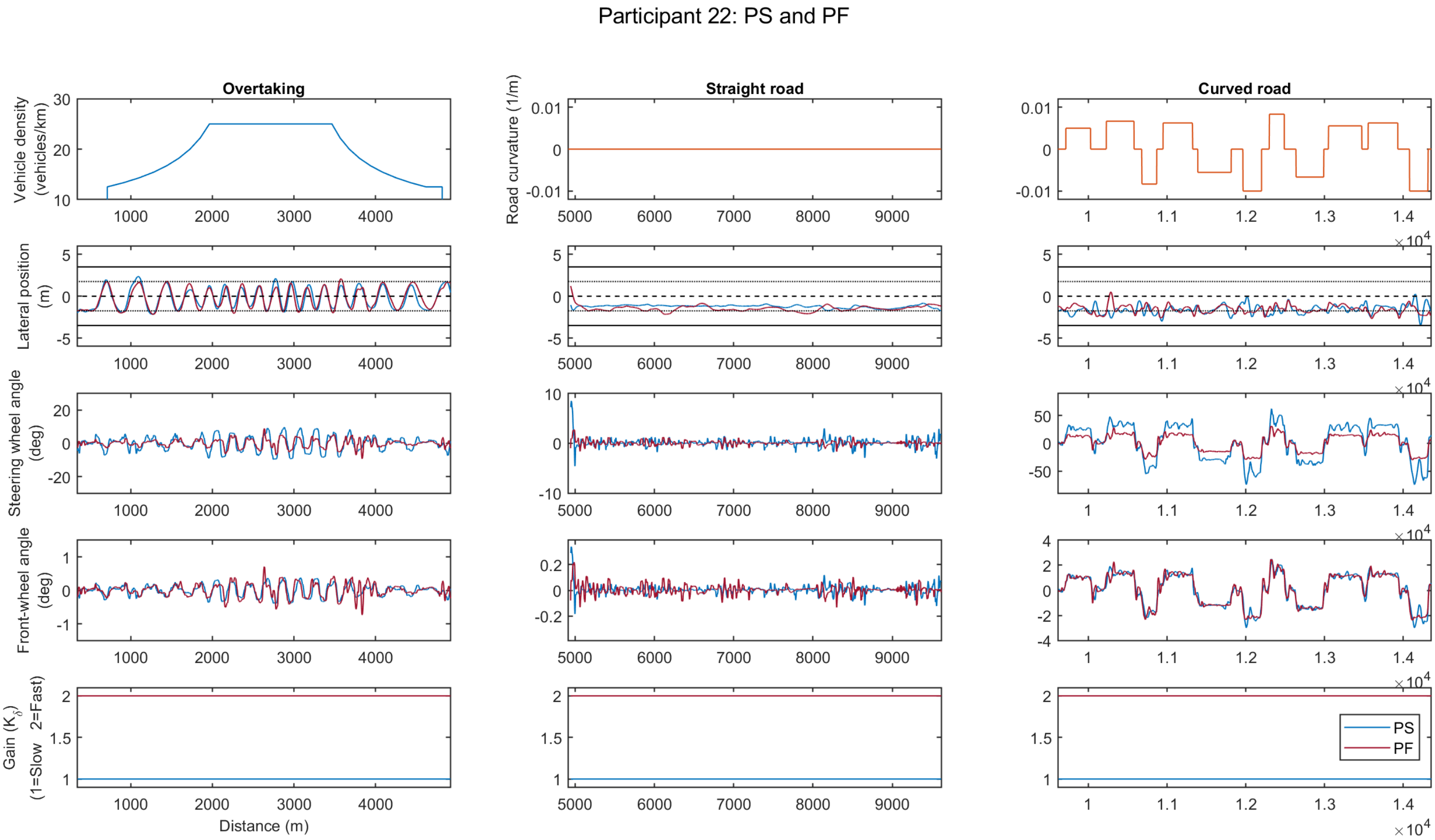


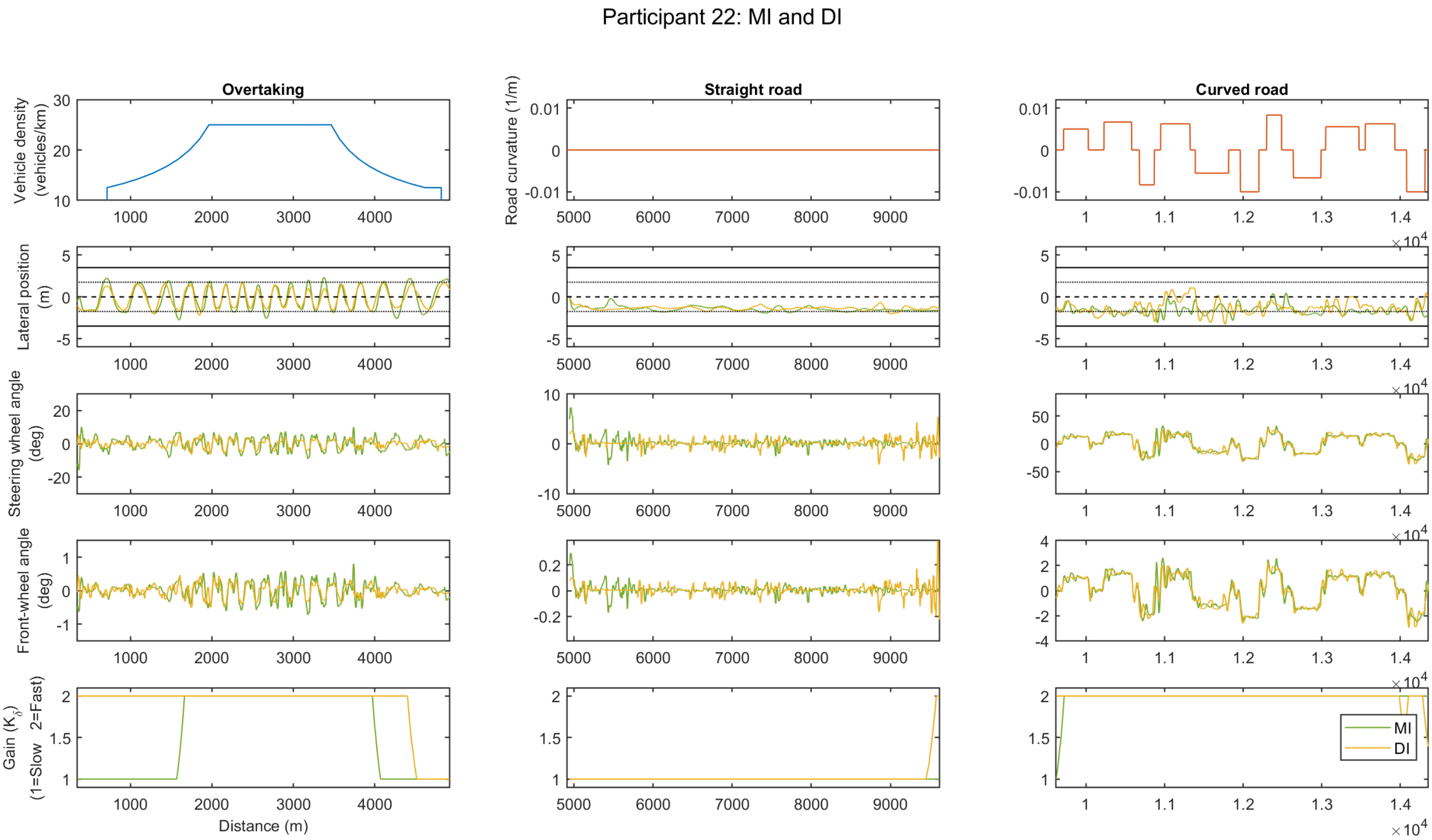
Participant 21: PS and PF

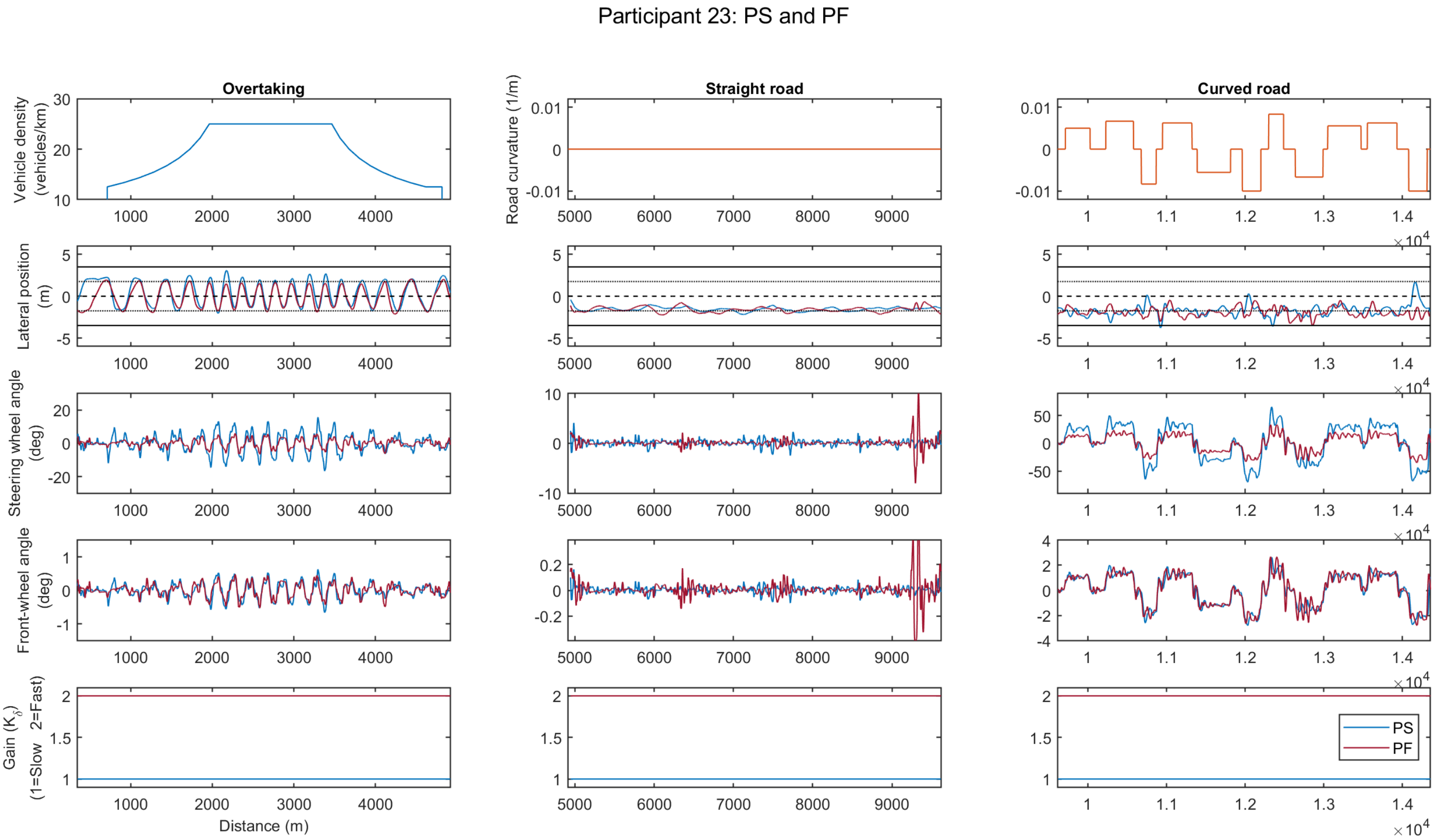


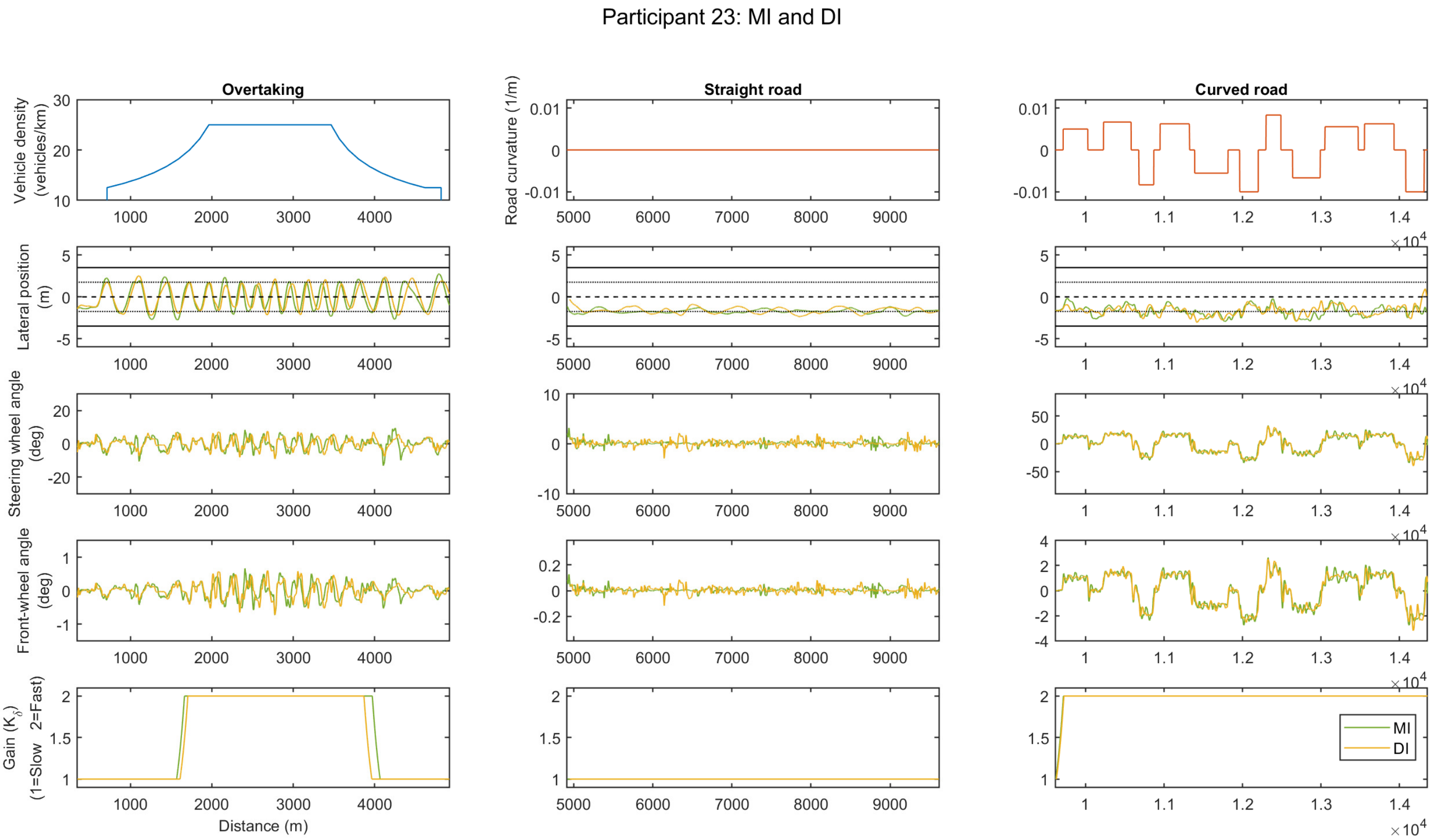
Participant 21: MI and DI



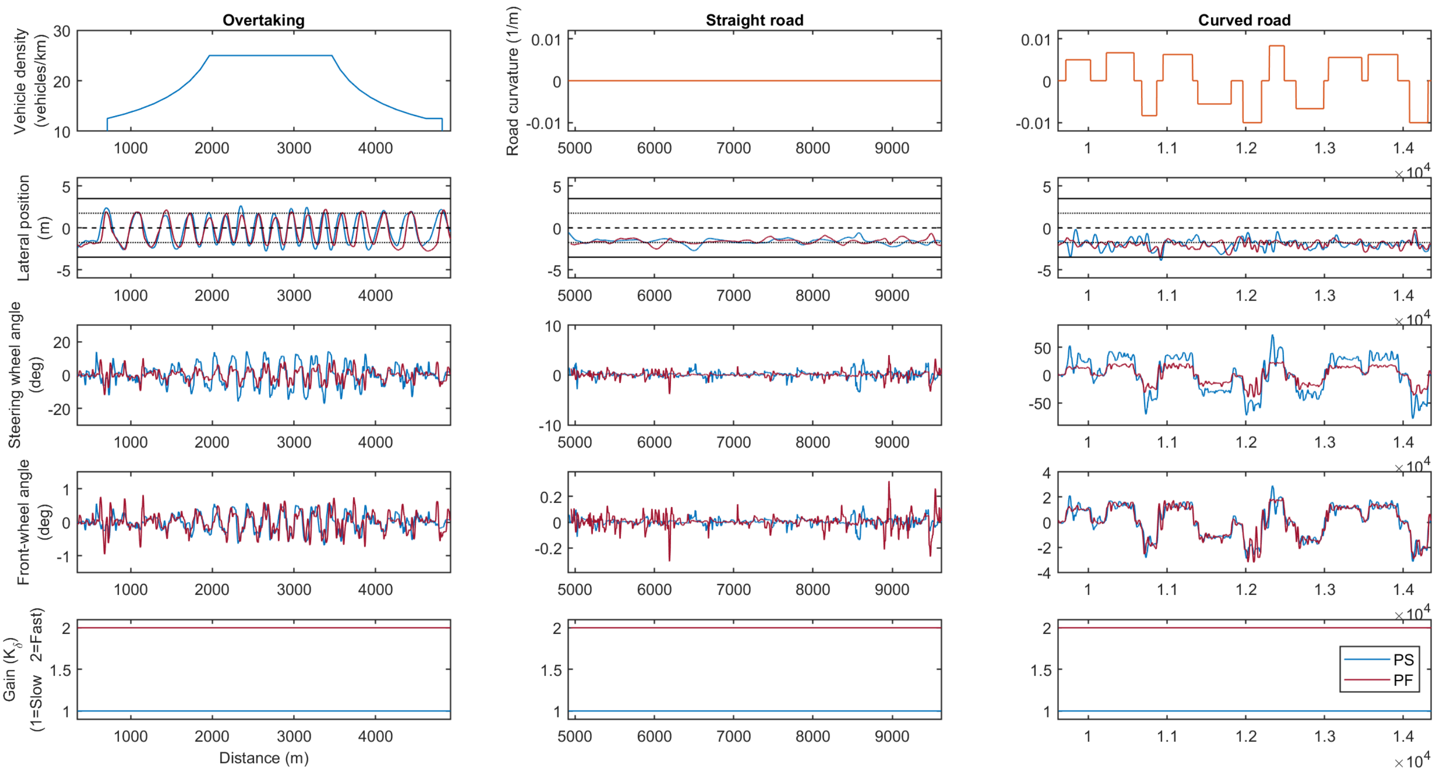

Participant 22: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF


Participant 22: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI


Participant 23: PS and PF
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
PS
PF


Participant 23: MI and DI
Overtaking
Straight road
Curved road
Vehicle density (vehicles/km)
Road curvature (1/m)
Lateral position (m)
Steering wheel angle (deg)
Front-wheel angle (deg)
Gain (K_δ) (1=Slow 2=Fast)
Distance (m)
MI
DI

Participant 24: PS and PF



Participant 24: MI and DI