The impact of steering ratio variability to road profiles on driver acceptance and driving behaviour

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TU Delft

The impact of steering ratio variability to road profiles on driver acceptance and driving behaviour

Thesis

By

Roderick Kroes

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Preface

This thesis concludes the Master programme Vehicle Engineering of Mechanical Engineering at the Delft University of Technology. The followed specialisation programme is Human Factors and supplemented with vehicle dynamics courses. The knowledge in those topics forms the fundament of this thesis.
That combines to a further look into steering ratio variability to road profiles and evaluation of driver acceptance and driving behaviour.

Roderick Kroes
Rotterdam, May 9th 2019

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Thank you all !

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Content

TU Delft

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Abstract— **Variable steering systems have the ability to change the ratio between the steering wheel and the front wheels while driving. These adjustable steering systems have led to an improvement in traffic and road safety and decrease in driver's workload. A previous study concludes that driver steering behaviour is significantly dependent on vehicle speed and road curvature (number and sharpness of bends). Interestingly, variable steering ratio systems often depend on speed but not on road curvature. Variable steering ratio dependent on road curvature possibly influences driving behaviour and might be desirable for safety and driver acceptance. The goal of this research is to investigate driver acceptance and driving behaviour for two separate steering ratios (1:12 and 1:40) and two different road profiles (i.e. specific curvatures straight highway and curvy country road) at a constant speed. We hypothesize that on a curvy country road low steering ratio (1:12) leads to higher safety margins and subjective ratings, whereas on a straight highway a high steering ratio (1:40) leads to higher safety margins and subjective ratings. Therefore we conducted a within-subject driving experiment (N=24) in a fixed-based passenger vehicle simulator at constant speed. The results show that on a country road a vehicle with a low steering ratio increases time-to-line-crossing (TLC) safety margins and increases self-reported subjective ratings compared to the high steering ratio setting. Likewise, on a highway, a vehicle with a high steering ratio leads to higher safety margins and comfort rating compared to a low steering ratio. Thereby it can be concluded that steering ratio variable to the road profile improves safety and acceptance. These results provide promising evidence to make steering systems adaptable to road profile (e.g. steer-by-wire and active rear wheel steering).**

***Keywords*— Driver acceptance, steering ratio, driving simulator, driver-in-the-loop experiment**

I. Introduction

Innovative steering systems are variable steering ratio or steer-by-wire system. They can lower driver's steering effort, by means of electric motors assisting with the steering movements. And they can improve lateral responsiveness, stability or manoeuvrability of the vehicle [1]. That assistance of the driver can decrease driver's workload and improve of 'traffic and road safety' [2]. One of the parameters that the variable steering systems can influence is the steering ratio, which is the ratio between the steering wheel angle input and road wheel angle output [3]. High steering ratio means little reaction of the vehicle to a steering wheel movement, whereas a low steering ratio means a high response of the vehicle to steering wheel movement.

The model of driver steering behaviour of Donges [4] can be used to improve variable steering systems. The model is significantly dependent on vehicle speed and road curvature (number and sharpness of bends). Steering systems can be variable to speed in order to adapt to the changes of vehicle dynamic handling characteristics due to change of speed. That adaptation of steering ratio has promising results, because it can reduce steering input and improve lane-change performance at low and high speed [5]–[7]. That means that the "driver has to perform less adaptive work" [7]. However steering systems variable to road curvature are not yet been investigated.

The road curvature is the forcing function in the control task for lane following [4]. The driver's control actions are highest for sharp curves, which require large steering-wheel amplitudes. It means that for sharp curves "steering-wheel velocities are highest and Time-Lane-Crossing's (safety margin expressed in time from steering input to lane departure) are shortest for the sharpest curves" [8]. Steering systems can increase the steering sensitivity (responsiveness) of a vehicle for sharp curves [1], [9]. That reduces the high steering wheel velocities and may reduce the adaptive work for the driver. However high steering wheel sensitivity is suggested to cause high workload for driving on a straight highway [5], [6]. A variable steering system may dissolve this trade-off by changing the steering ratio at a highway. We focus on steering systems variable to road profiles. Indication of specific (change of) road curvature (two different road profiles) can be triggered and communicated with geo-fencing technique. Geo-fencing is a GPS-based system that can communicate with the steering system on which road (highway/country road) the car is driving [10].

The subjective evaluations of steering systems need to be researched in more depth [11]. Adjusting the steering sensitivity is likely to cause a reciprocal effect on the driver steering input magnitude [4]. Adaptation of the steering system to the lateral deviations and yaw angle errors reduces workload, but the driver subjective response was not measured [2]. Adjusting the steering ratio to other parameters (e.g. speed or driving mood) has influence on the driver's subjective driving experience [12], [13]. We evaluate subjective driver acceptance of the steering system.

Currently, information in literature is not sufficient to answer the question what effects steering sensitivity variable to road profiles has on driver acceptance and whether drivers change their driving behaviour (e.g. in terms of TLC) due to different steering sensitivity. The goal of this research is to investigate driver acceptance and driving behaviour for two steering ratios and two different road profiles at a constant speed. The focus of this research is twofold. The first focus is to investigate the effect of variable steering ratio on driver acceptance. The second focus is to investigate whether variable steering ratio affects the objective driving behaviour.

We hypothesize on the one hand that on a country road high responsiveness and low steering ratio is desirable (Fig.1). The low steering ratio could potentially lower the steering wheel velocities and time-to-line-crossings. That might lead to lower physical workload, a higher driver acceptance and driving behaviour, compared with a high steering ratio. On the other hand, on a highway less sensitive steering is desirable, because that could lower mental workload and make the vehicle easier to control precisely.

We chose two fixed steering ratios. The steering ratio of around 1:22 at steady state would be preferred [14]. The steering ratios in this experiment are 1:12 and 1:40. We emphasize the difference between the ratios, within realistic boundaries, to clarify for all kinds of participants in this simulator experiment [15], [16].

The goal of this research is to investigate driver acceptance and driving behaviour for two steering ratios and two different road profiles at a constant speed. Therefore we conducted a within-subject driving experiment (N=24) in a fixed-based passenger vehicle simulator at constant speed (80km/h). Two fixed steering ratios are tested on two roads with different curvature (curvy country road, straight highway). Safety margin is measured in terms of time-to-line-crossing (TLC). Subjective driver experience is captured in self-reported questionnaires.

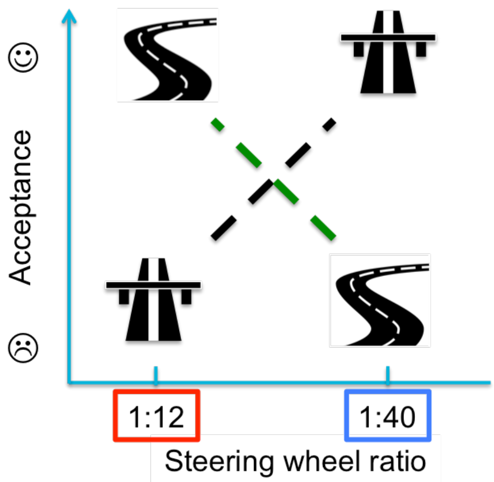

Fig. 1. Hypothesis for driver acceptance for steering wheel ratios (1:12, red, and 1:40, blue) at different road type (highway and country road). We hypothesize that on a country road a vehicle has preferably low steering ratio setting (1:12 - high responsiveness and steering sensitivity) to improve driver acceptance and driving behaviour compared with a high steering ratio setting. Likewise, on a highway a vehicle with high steering ratio (1:40 - less sensitive and responsiveness) is desirable and may improve driver acceptance and driving behaviour, compared to a low steering ratio.

II. Method

A. *Participants*

24 participants volunteered to take part in the experiment (5 females, one 'prefer not to say'; mean age 25.7 std5.7). 18 participants were students at the Delft University of Technology. The requirement was to have a driver's license. On average the participants held their driver's license for 6.6 (std6) years. 12 participants reported to drive at least once a week on average for the past 12 months and only 3 participants reported to drive less than once a month. The Human Research Ethics committee of the Delft University of Technology approved this research. All participants signed the informed consent form.

B. *Apparatus*

The Human-in-the-Loop experiment was conducted in the fixed-based simulator at the faculty of Aerospace Engineering of Delft University of Technology. The set-up consists of an electrically adjustable car seat, steering wheel, dashboard 12" LCD display with speed and revolution indicator and three beamers. The electrically actuated steering wheel (MOOG FCS ECol8000S) is locally controlled by a control loading computer at 2500Hz to ensure a smooth steering wheel feeling. Data were recorded at 100Hz. The virtual driving environment was projected LCD projectors with a 180° horizontal and 40° vertical field-of-view and refreshed at 50Hz.

C. *Vehicle motion*

A two-track vehicle model simulates the vehicle dynamics. The vehicle drives at constant speed of 80km/h and is 1.8m wide (Appendix D-Vehicle).

D. *Steering system*

The independent variable is the ratio between the steering wheel angle and the angle of the front wheels. The ratios tested in this paper are 1:12 and 1:40. The ratio 1:40 is tuned to be able to drive the country road curvature within a steering wheel angle of roughly 90 degrees to avoid a necessity to change from the standard manual steering wheel grip (10-to-2 grip) [17]. The ratio 1:12 is tuned to have high steering sensitivity, but avoid a nervous or unstable vehicle. The roughly approximated steering sensitivities of the ratios are within realistic boundaries 0.7g/100deg (SR 1:40) and 2g/100deg (SR 1:12), where lateral acceleration are based on the simulated vehicle model (Appendix D-Vehicle) [15], [16].

E. *Steering wheel feeling*

Steering wheel stiffness is tuned independently from the steering ratio. Normally, adjustment of the steering ratio changes the transmitted torques to the steering wheel and therefore changes the steering wheel stiffness. Since the goal is to study the effect of steering ratio, the steering stiffness setting is kept the same for both ratios. The steering wheel would increase linear, as the vehicle remains in the linear tire region. However that would cause unrealistic torques for the steering 1:40 on the country road. Therefore the stiffness is designed with a cut-off at 3Nm (Fig.2).

F. *Road design*

Three road designs are used: straight highway, curvy country road and a combined training road (Appendix E-Road). The road consists of two lanes and each lane is 3.6m wide. The highway road is a straight section of 11.2 km long.

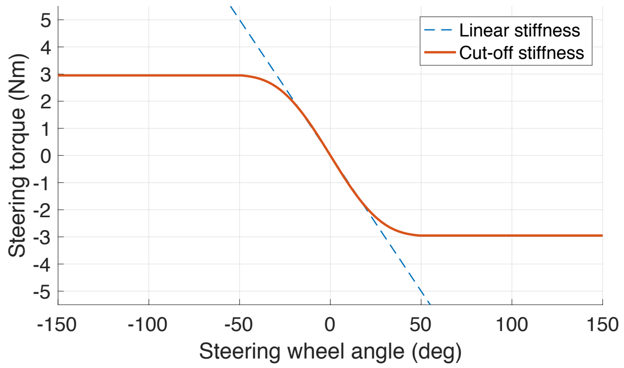

Fig. 2. Steering wheel torque (Nm) (i.e. self-alignment torque) vs. steering wheel angle (deg). Steering wheel stiffness is designed with a cut-off at 3Nm to avoid high unrealistic high torques for SWA above 50deg.

The country road is 10.8 km long having 46 curves. The road curvature of the country road has been made high to make the steering demand high. The curve radius for speed of 80 km/h according to Dutch public road regulations [18] would be 345 meter, but the vehicle and tire dynamics accomplish a radius of 60meters at that speed (Appendix E-Road). The training and country road radii are both between 100 and 220 meter. The road is adjusted to the vehicle to stay in the linear vehicle dynamic region (Appendix E-Roads). The training road consists of 5.5km straight section (4min) and 4.0km curved section (18 curves, 3min) with the similar curvature as the country road. The highway condition contains three take-over manoeuvres, which involves a lane change to the left lane and back and takes 40 seconds each.

G. Procedure

The participants were asked to read and sign the 'Informed consent form' and read the 'Acceptance questionnaire' to make them aware of the type of questions and the steering task (Appendix H-Questionnaires). Before the training the participants received verbal driving instructions (Appendix F-Instructions). The participant trained with the steering ratio setting for 7 minutes to avoid learning effects [19]. After the first training a questionnaire is filled in concerning the participants previous driving experience (Appendix H-Questionnaires). Next, the participants drove the two road profiles (Highway and Country road), both followed by answering the four subjective questionnaires (Appendix H-Questionnaires). Then the participants were trained for the other steering ratio setting and subsequently drove the two road profiles again. The complete sequence can be varied in 8 different orders and ensures full counterbalancing over all participants (Appendix F-Instructions).

H. Data Processing

a) Subjective measures

Short Dundee 3-State Stress-test measures engagement, distress and worry in 24 questions [20], [21]. Each measure category has eight questions. All questions are answered on a 5-point Likert-scale, from 0 till 4 (Definitely false 0, Somewhat false 1, Neither true nor false 2, Somewhat true 3, Definitely true 4).

Acceptance questionnaire consists of eight statements with answers on a 7-point Likert-scale from (-3) Totally disagree, disagree, somewhat disagree, neither agree nor disagree (0), somewhat agree, agree to totally agree (3) (Appendix H-Questionnaires). The questions are: '1. I had the vehicle safely under control. 2. The control of the vehicle felt realistic. 3. I felt comfortable. 4. The vehicle responded realistically to steering movements. 5. I found the vehicle easy to control. 6. I found the vehicle course stable. 7. How soon does the vehicle react after you turn the steering wheel? (scale: delayed – quick) 8. How do you like this configuration of the steering overall? (scale: poor – good)' [22]–[24].

NASA-TLX workload is used to assess cognitive workload [25].

Participants indicate their simulator sickness on a nausea questionnaire with a scale from 1 to 6 (1 No sign of symptoms, 2 Arising symptoms, 3 Slight nausea, 4 Nauseous, 5 Very nauseous, retching, 6 Throwing up).

b) Objective metrics

Steering wheel angle

- the root mean squared error
- the reversal rate.

Steering wheel torque

- the root mean squared error value indicates the work that the participants applied.

Lateral position with respect to the centre of the lane is used for the following two metrics.

- Standard deviation of the lateral position captures the driving behaviour of the participant
- Mean peak-to-peak-time of lateral position is the time between peaks, which are local min/max that have a lateral spacing of more than 0.1m (similar to steering reversal rate).

Time-to-line-crossing identifies the safety margins. That means the time to lane departure without further action. The Time-to-line-crossing is calculated with the trigonometric method, which takes the curvature of the vehicle trajectory into account [26].

- The TLC value is used for the mean lowest 15-percentile [27].

I. Statistical analysis

The effect of the two steering ratios is compared pairwise on the two road profiles separately and within subjects. The subjective measures are captured in a discrete Likert-scale, so a discrete compatible test is needed. The distribution of metrics over all participants is non-parametric. The Wilcoxon signed rank test is used for all comparisons.

The effect size was calculated according to $dz=z/\sqrt{n}$, where n is the number of observations (n=48: 2 conditions (steering ratio) x 24 participants) and z is the z-value of the approximated Wilcoxon signed rank test. Matlab R2016b (MathWorks, Inc.) is used for all analyses.

III. Results

Table 1 displays all metrics with means, standard deviations and results of Wilcoxon's paired comparisons between steering ratios 1:12 and 1:40.

A. Country road

a) Acceptance

In the acceptance questionnaire drivers indicated that the subjective rating of the system (question 8) of the 1:12 steering ratio configuration is higher than 1:40 (Fig. 3). The same result is found for the three other questions: 'safely under control' (1), 'comfortable' (3), and 'easy to control' (5). No difference is found for question 6 between the steering ratios. The Dundee 3-State Stress-test shows a lower level of distress experienced by the participants for driving on the country road with the 1:12 ratio. No differences were found for engagement or worry though.

b) Driving behaviour

The safety margin TLC (mean of lowest 15%) is higher for 1:12 steering ratio on the country road (Fig. 7). The standard deviation of the lateral position and reversal rate of the steering wheel angle are lower for 1:12 steering ratio on the country road.

c) Workload

On the country road the NASA-TLX subjective workload with a 1:12 ratio is lower than for the 1:40 ratio. The root mean squared error of the steering wheel angle and torque are both lower for 1:12 ratio. acceptance

d) Questionnaire results

The results of the acceptance questionnaire also indicate higher positive responses for steering ratio 1:12 on the statements 'The control of vehicle felt realistic' (2), 'The vehicle responded realistically to steering movements' (4) and on the question 'How soon does the vehicle react after you turn the steering wheel' (7).

e) Correlation

The subjective metrics correlate weakly with objective metrics in the Spearman correlation matrix; all below (or equal to) 0.5 (Appendix B-Correlations: Table B-2 and B-4). The objective measures correlate well among each other, so do the subjective measures.

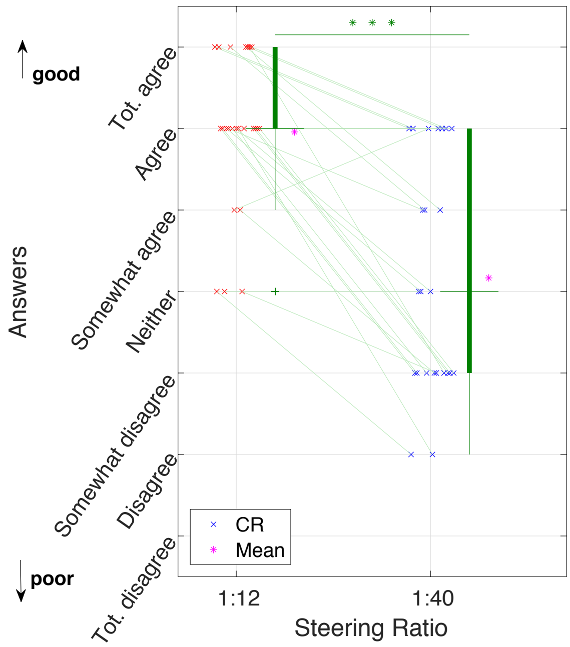

Fig. 3. Overall steering rating question 8 'How do you like this configuration of the steering overall?' from self-reported acceptance questionnaire for two steering ratios 1:40 (blue) 1:12 (red) on country road (CR). *** significance level of p<0.001. Boxplot of median, 25-percentile and 75-percentile.

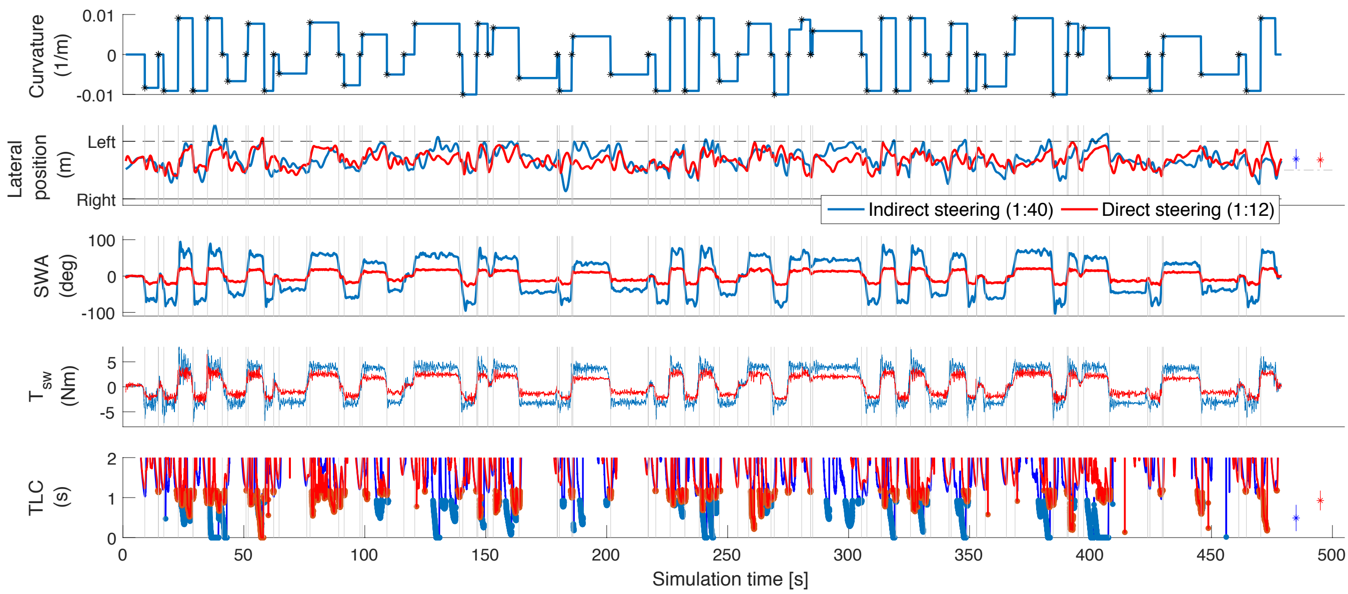

Fig. 4. Typical driving for country road (CR) of participant 7 From top to bottom: Curvature (1/radius (m)), lateral position (m) with on the right, mean and std w.r.t. lane centre, SWA, steering wheel angle (deg), Tsw, steering wheel torque (Nm) and TLC, Time-to-line-crossing (s) – lowest 15% in bold – with on the right, mean and std for Simulation time (s) with two steering ratios 1:40 (blue) 1:12 (red) incl. vertical lines for change in curvature.

Table 1: Means (M), standard deviations (SD), effect sizes (dz), and results of the Wilcoxon paired within-subject test (p) per dependent measure

N=24		**Highway**							
		1:12	1:40			1:12	1:40		
		M (SD)	M (SD)	p	d_z	M (SD)	M (SD)	p	d_z
Dundee 3-state	Engagement	22.91 (4.968)	22.79 (4.818)	0.8305	0.03	17.04 (6.950)	16.16 (7.025)	0.121	0.22
questionnaire	Distress	5.041 (4.005)	7.833 (4.949)	**0.0054**	-0.40	3.958 (3.700)	3.083 (2.652)	0.2861	0.15
	Worry	8.666 (6.551)	9.208 (6.269)	0.477	-0.10	8.750 (6.515)	8.708 (5.782)	0.9517	0.01
Acceptance	1 safely control	2.250 (0.607)	1.208 (1.473)	**0.0015**	0.46	2.166 (0.868)	2.625 (0.494)	**0.0168**	-0.35
questionnaire	2 vehicle realistic	1.833 (1.049)	0.291 (1.680)	**0.0016**	0.46	1.458 (1.062)	1.666 (1.307)	0.4585	-0.11
	3 comfort	1.916 (0.928)	1.083 (1.411)	**0.0115**	0.36	1.875 (1.361)	2.333 (0.761)	**0.032**	-0.31
	4 steering realistic	1.875 (0.740)	0.666 (1.551)	**0.0018**	0.45	1.583 (1.212)	1.750 (1.293)	0.6362	-0.07
	5 easy control	2.041 (0.999)	0.375 (1.636)	**3.66E-04**	0.51	1.833 (0.963)	2.375 (0.646)	**0.0184**	-0.34
	6 stable	1.458 (1.318)	1.125 (1.295)	0.2837	0.15	1.291 (1.706)	2.541 (0.509)	**1.30E-03**	-0.46
	7 Delay	2.166 (0.916)	0.541 (1.768)	**3.43E-04**	0.52	2.208 (1.215)	0.833 (1.578)	**7.83E-04**	0.48
	8 Overall rating	1.958 (0.954)	0.166 (1.434)	**9.11E-05**	0.56	1.208 (1.473)	1.625 (1.312)	0.3912	-0.12
NASA-TLX	Mean	28.40 (15.79)	37.70 (16.03)	**2.52E-04**	-0.53	17.95 (11.24)	16.70 (12.42)	0.33	0.14
	Mental	42.29 (26.33)	50. 83 (23.62)	**0.027**	-0.32	26.66 (27.13)	24.16 (25.81)	0.1142	0.23
	Physical	17.91 (15.45)	34.16 (27.61)	**6.57E-04**	-0.49	13.95 (20.05)	16.45 (21.84)	0.3581	-0.13
	Temporal	35.00 (24.62)	40.41 (26.28)	0.1127	-0.23	13.75 (14.76)	13.12 (17.49)	0.1922	0.19
	Performance	23.33 (21.09)	31.45 (17.03)	**0.0465**	-0.29	14.79 (17.35)	15.20 (16.18)	0.5994	-0.08
	Effort	37.70 (23.45)	48.75 (19.74)	**0.0098**	-0.37	19.37 (18.31)	17.70 (19.10)	0.7481	0.05
	Frustration	14.16 (15.51)	20.62 (18.31)	**0.0375**	-0.30	19.16 (22.77)	13.54 (12.89)	0.2384	0.17
SW Torque	RMS	1.937 (0.189)	3.408 (0.041)	**1.82E-05**	-0.62	0.359 (0.014)	0.374 (0.022)	**3.18E-04**	-0.52
SW Angle	Reversal Rate	0.684 (0.165)	0.834 (0.176)	**3.43E-05**	-0.60	0.097 (0.104)	0.182 (0.160)	**0.0034**	-0.42
	RMS	15.31 (0.176)	51.36 (0.777)	**1.82E-05**	-0.62	0.547 (0.197)	0.827 (0.338)	**3.95E-04**	-0.51
Lateral	Standard Deviation	0.296 (0.059)	0.354 (0.098)	**0.0051**	-0.40	0.170 (0.045)	0.172 (0.057)	0.8639	-0.02
position	Num. of peaks	226.5 (27.79)	231.3 (27.24)	0.1885	-0.19	55.62 (17.84)	42.70 (13.21)	**2.93E-04**	0.52
	Peak-to-peak-time	1.906 (0.229)	1.934 (0.246)	0.6476	-0.07	8.092 (3.072)	10.04 (4.396)	**0.0056**	-0.40
Time-Lane-Crossing	Mean lowest 15%-tile	0.791 (0.216)	0.582 (0.272)	**1.02E-04**	0.56	3.818 (1.126)	5.501 (2.663)	**3.96E-04**	-0.51
Lat. Acceleration	RMS	3.360 (0.036)	3.383 (0.049)	**0.0018**	-0.45	0.096 (0.043)	0.048 (0.021)	**7.14E-05**	0.57
YawRate	RMS	8.693 (0.104)	8.750 (0.137)	**0.0047**	-0.41	0.271 (0.122)	0.132 (0.059)	**4.97E-05**	0.59

Bold text has significance level of p lower than 0.05, RMSE: Root mean square

B. *Highway*

Objective metrics are based on data without take-over manoeuvre and few seconds at start and end, among which is TLC (Fig. 4). Take-over manoeuvres are analysed separately (Appendix A-Take-over).

a) Acceptance

For the highway condition the results of the acceptance questionnaire show that participants felt more 'comfortable' (3) with the steering ratio 1:40 than with 1:12 ratio configuration (Fig. 5). The same result was found for the questions 'safely under control' (1), 'easy to control' (5) and 'I found the vehicle course stable' (6). No difference is found for question 8 between the steering ratios.

The Dundee 3-State Stress-test does not show any difference for the experienced engagement, distress and worry.

b) Driving behaviour

The safety margin TLC (mean of lowest 15%) is higher for 1:40 steering ratio on the highway (Fig. 7). Also the peak-to-peak-time of the lateral position is higher for 1:40 steering ratio.

c) Workload

The NASA-TLX subjective workload questionnaire results show no difference. The reversal rate and root mean squared error of the steering wheel angle and torque are higher for 1:40 ratio.

d) Questionnaire results

The acceptance questionnaire results do not show differences for the questions 'The control of vehicle felt realistic' (2) and 'The vehicle responded realistically to steering movements' (4). On the contrary the question 'How soon does the vehicle react after you turn the steering wheel' (7), is answered significantly lower for 1:40.

e) Correlation

The subjective metrics correlate weakly with objective metrics in the Spearman correlation matrix; all below (or equal to) 0.5 (Appendix B-Correlations: Table B-3 and B-5). The objective measures correlate well among each other, so do the subjective measures.

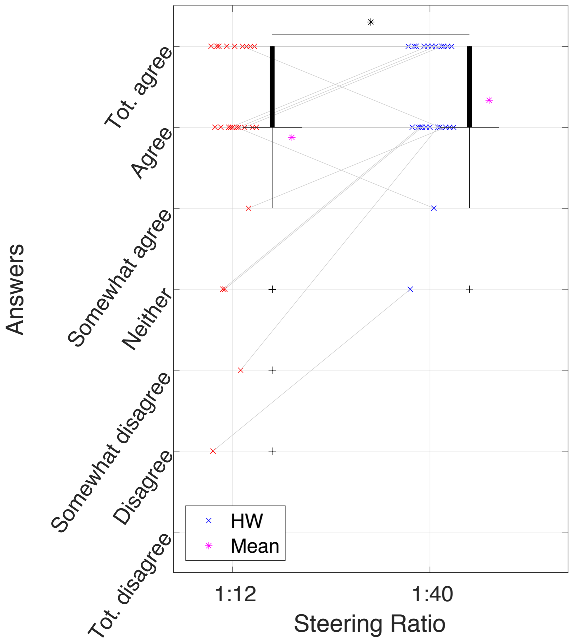

Fig. 5. Comfort rating statement 3 'I felt comfortable.' from self-reported acceptance questionnaire for two steering ratios 1:40 (blue) 1:12 (red) on highway (HW). * significance level of p<0.05. Boxplot of median, 25-percentile and 75-percentile.

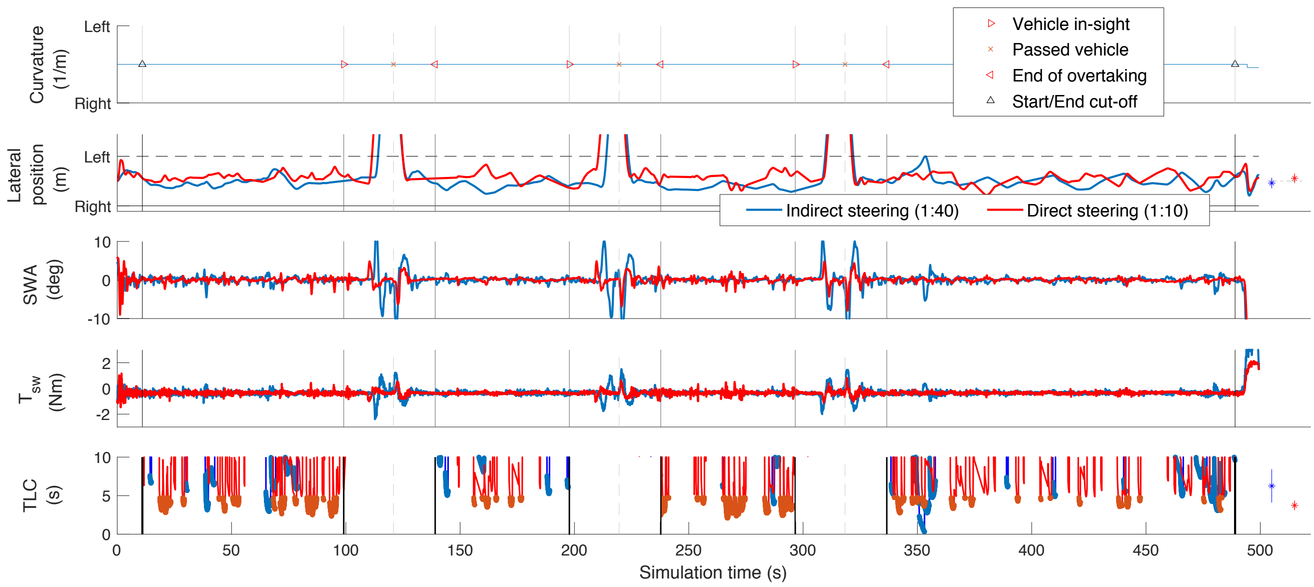

Fig. 6. Typical driving for highway (HW) of participant 11. From top to bottom: Curvature (1/radius (m)) and take-over start/end, lateral position (m) with on the right, mean and std w.r.t. lane centre (without change to left lane for take-over manoeuvres (Appendix A)), SWA, steering wheel angle (deg), Tsw, steering wheel torque (Nm) and TLC, Time-to-line-crossing (s) – lowest 15% in bold – with on the right, mean and std for Simulation time (s) with two steering ratios 1:40 (blue) 1:12 (red) incl. vertical lines for take-over manoeuvre start/end and start/end cut-off for analysis.

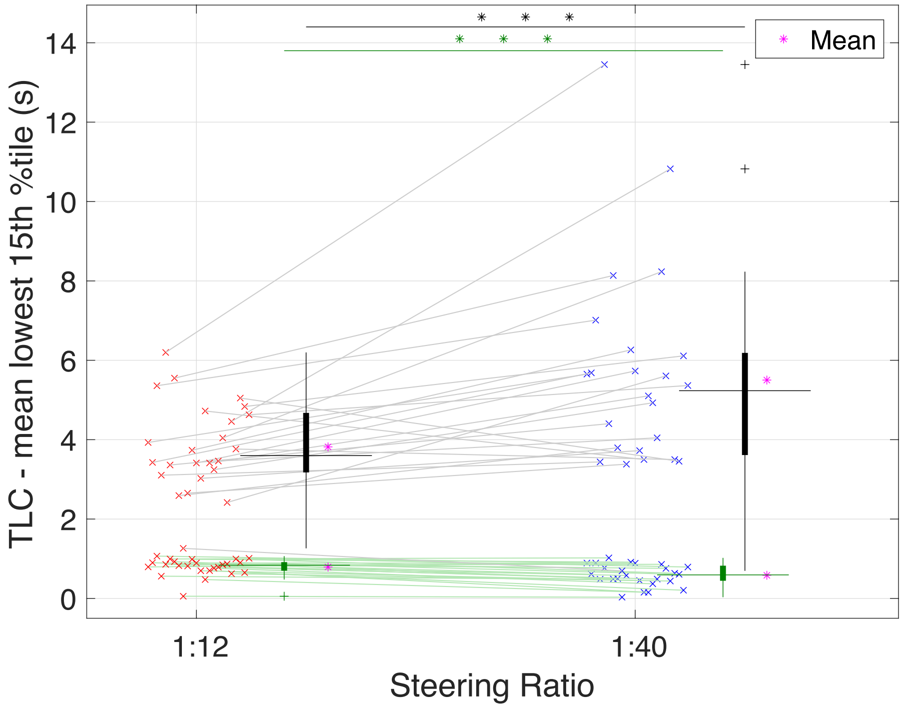

Fig. 7. Typical Most critical safety margins (mean of lowest 15-percentile of TLC) for two steering ratios 1:40 (blue) 1:12 (red) on the highway (HW, black) and the country road (CR, green). *** significance level of p<0.001. Boxplot of median, 25-percentile and 75-percentile.

C. Supplementary analysis

a) Nausea

None of the participants experienced more nausea symptoms than 'arising symptoms (like a feeling in the abdomen), but no nausea'.

IV. Discussion

The goal of this research is to investigate driver acceptance and driving behaviour for two steering ratios and two different road profiles at a constant speed. We investigate the effect of variable steering ratio on driver acceptance and whether variable steering ratio affects driving behaviour.

A. Effects on driver acceptance

The two steering ratios have effect on driver acceptance. The steering ratio 1:12 on the curvy country road results in a higher overall subjective rating in the acceptance questionnaire. On the straight highway steering ratio 1:40 results in higher rating of comfort just as a higher results of question 6 'I found the vehicle course stable'. The participants have sufficient driving experience (licensed for 6.6 ±6 years and 21 participants drove more than 1.000km past 12 months) to assess and compare the driving situations well. The effect of two steering ratios on driver acceptance is similar to literature with different steering sensitivity at different speeds [13], and variable to different moods [12] as where we test at one speed and no driving moods, but at different road profiles. Both higher driver acceptance and easier control of the vehicle (more precise) is in agreement with the hypothesis that steering ratio 1:12 on the country road and steering ratio 1:40 on the highway increases driver acceptance.

B. Safety margin and driving behaviour on the country road

The two steering ratios also have effect on driving behaviour. Sharp curves require large steering wheel amplitudes and show TLC's to be shortest [8]. We found that on the country road the steering ratio 1:12 showed an increase in safety margin (mean of lowest 15% of TLC). This safety margin may be perceived by the driver and could have thereby contributed to the increase in drivers' acceptance. At a higher TLC the time buffer to the lane boundary is higher and this may cause that drivers indicated to have experienced less distress and workload (Table 1.).

Further results showed that steering ratio 1:12 on the country road decreased the standard deviation of the lateral position (SDLP). Steering ratio 1:12 enables the drivers to follow the road curvature of the country road closer. From the measurements during the experiment it appears that with the steering ratio 1:12 the distance from the lane centre varies less than with the steering ratio 1:40, the SDLP is lower. TLC and SDLP together with the steering wheel angle reversal rate (SRR) show improved results in safety margin and driving behaviour with the 1:12 steering ratio, similar to driver acceptance results. A similar improvement is seen in literature for a steering system adaptable to the lateral deviations and yaw angle errors. That is measured in cost function of the lateral position, integral of steering wheel angle and steering wheel speed, which leads to reduced driver's workload and improved path-following [2]. The higher overall subjective rating, comfort, cognitive workload and distress are all in favour of steering ratio 1:12 at the country road.

C. Safety margin and driving behaviour on the highway

The two steering ratios have also effect on driving behaviour on the highway. On the highway, the steering ratio 1:40 increased the safety margin (mean of lowest 15% of TLC). The ratio 1:40 also increases the peak-to-peak-time of the lateral position with respect to 1:12 ratio, indicating a less swerving in the lane. Both TLC and peak-to-peak-time show increase with the 1:40 steering ratio on the highway. Interestingly, that differs from literature, where TLC level has been concluded to be roughly constant at various speeds, a constant steering ratio on a straight highway [28]. Possibly the steering ratio 1:40 on the highway increases TLC by extending the 'open-loop control period' without steering action and simplifies the 'correctional actions' of the driver. That might support the reasoning that steering ratio 1:40 on the highway makes it "easier to control the vehicle precisely" [6].

The TLC and peak-to-peak-time display improved results, similar to some driver acceptance measures on the highway. Higher safety margin and peak-to-peak-time for lateral position show the same trend as the acceptance questions on comfort (3), controllability (1 and 5) and course stability in favour of steering ratio 1:40 on the highway. Interestingly, participants also seem to prefer the steering ratio 1:40, despite the higher driver steering wheel input effort. The RMSE value of steering wheel torque, reversal rate and RMSE value for angle are higher for steering ratio 1:40. The reason that the participants seem to prefer higher steering effort might be that the difference is relative, because the absolute values of steering wheel input effort are low with respect to the country road, approximately five to ten times lower (table 1). The steering effort for the highway is apparently experienced as low relative to the effort experienced on country road. Likewise, subjective workload does not indicate a significant difference. The driver might also not experience the higher steering effort as workload, because of the pauses, 'open-loop control periods' (not performing driving control actions), between the corrections [28].

D. Limitation on this study

The results from this study must be seen in perspective with the some limitations.

a) Evasive manoeuvres with low steering responsiveness

On the highway steering ratio 1:40 results in higher rating of comfort just as a higher results of question 6 'I found the vehicle course stable'. On the contrary, a lower stability feeling for steering ratio 1:12 may reflect the descriptions on 'over-sensitive steering on highway' in literature [5], [6]. Millsap & Law state that high steering sensitivity is "perceived by drivers as difficult to maintain directional control during highway driving". Likewise, Shimizu et al. [6] state that high steering sensitivity "can produce increased mental workload for drivers". The participants also indicated that the high steering sensitivity led to less ease of control (question 5). If the steering sensitivity is set to the high curvature (country road) setting (1:12), the steering is too sensitive while driving on the highway.

That is the result of this experiment where the highway is straight and has three anticipated take-over manoeuvres. However, in reality situations occur such as evasive manoeuvres, which actually require high sensitivity of the vehicle to avoid a collision. So future work would need to investigate the limits of these steering ratios in such situations.

b) Steering stiffness

Steering stiffness design could further improve the effects of steering system. Steering stiffness reality is limited, because of the designed stiffness cut-off. The steering stiffness should be linear in the linear operational region of vehicle and tire dynamics. However that would cause a twice as high torque for a twice as big steering angle due to a difference in steering ratio. Drivers would not accept such high torques. We designed stiffness cut-off to avoid that these extremes would become a confounding factor in the research into steering ratio, because steering stiffness and torque are not the main subject in this study. With the cut-off design influences of steering stiffness are minimalized. The designed cut-off is at 3Nm for more than 50 degrees steering angle (Appendix D-Vehicle: Steering). Still some effect of larger steering stiffness above 50 degrees steering angle is visible due to hysteresis. However steering stiffness design could be improved in order to optimise the steering system impact on driver acceptance and driving behaviour e.g. with a steer-by-wire system [17].

c) Lateral acceleration

This experiment is performed in a fixed based simulator, where participants did not feel lateral accelerations. The fixed-base simulator has many advantages though, such as controllability, reproducibility, easy data collection and safe test environment [29]. Fixed-base simulators has relative validity, but has no (direct) validity for on-road driving [30]. On-road testing will have to verify the found effects. Shimizu et al. [14] suggested that lower lateral acceleration would be one of the benefits of a variable steering system. Extension of testing the system with lateral acceleration feeling (e.g. on-road driving) might therefore improve the results.

E. Transition of steering sensitivity

Future implementation of variable steering ratios in real vehicles, like 1:12 and 1:40, needs a discrete transition, from one ratio to another, or a continuously variable transition. Wang et al. [2] continuously adapts the steering sensitivity and the participants finish the task in the simulator without instability. Russell et al. [31] tested a transition of steering ratio in a real vehicle just before a single lane-change evasive manoeuvre and the results shows that the manoeuvre can still be performed although with lower performance in terms of SRR and RMS steering speed, because drivers needed time to adapt to the new steering ratio. A sudden steering ratio transition seems not to destabilise the driver-vehicle system, but gradual adaptation of steering ratio might cause less performance deterioration. Transitions and adaptability of the steering ratio system in the driver-vehicle system must be investigated further to accommodate future implementation in vehicles.

F. Path curvature adaptation

This approach of variable steering system to the path curvature (forcing function) seems to have similar effects as the more established approach dependent on speed, which compensates for changes in vehicle dynamics. The change of steering ratio according to the change of road profiles (curvature) seems to compensate for the responsiveness of vehicle which requires less adaptive work from the driver, similarly to speed dependent steering ratio [7]. The results of this research give reason to implement steering systems adaptive or variable to road profiles. Indication of specific (change of) road curvature (different road profiles) can be triggered and communicated with geo-fencing technique. Geo-fencing is a GPS-based system that can communicate with the steering system on which road (curvature) the car is driving [10].

This future system is hypothesized to increase safety margins and reduce workload. Therefore it may contribute to more traffic and road safety and more innovations in adjustable vehicle systems to come.

G. Future steering systems

These results provide promising evidence to design future steering systems adaptable to road profile. Adaptive input amplification might also be applicable to other variable steering gain systems such as active rear wheel steering and steer-by-wire. An adaptable steering system might be able to improve the driving feeling of a vehicle. That might open the opportunity to make a vehicle switch from feeling like sports car on a country road into feeling like a limousine on a highway [32]. The adaptable steering gain systems might combine the benefits of steering characteristics of a sports car and a limousine to possibly improve the driving feeling.

V. Conclusion

The goal of this research is to investigate driver acceptance and driving behaviour for two steering ratios and two different road profiles at a constant speed. We investigate the effect of variable steering ratio on driver acceptance and whether variable steering ratio affects driver's subjective acceptance, and driving behaviour for different road profiles.

From the results it can be concluded that steering ratio variable to the road profile can:

Lateral position with respect to the centre of the lane is used for the following two metrics.

- improve acceptance, specifically in overall likability on a curvy country road and comfort rating on straight highway,
- improve TLC (mean of lowest 15%) safety margin on a *curvy country road* with 30% (0.6→0.8s), as hypothesized, and
- improve TLC (mean of lowest 15%) safety margin on a *straight highway* with 40% (3.8→5.5s), as hypothesized.

High steering ratio has advantages on highway and low steering ratio has advantages on country road, so steering ratios variable road profile can improve both acceptance and driving behaviour.

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Appendix

A

Take-over

Take-over manoeuvres

Analyses

Time-to-Collision (TTC)[1],[2],[3] is a measure for driving behaviour in the overtake manoeuvres (Fig. A-1). TTC is calculated by the distance-to-collision (or distance headway) divided by the relative (/over-taking) speed between the ego and other car.

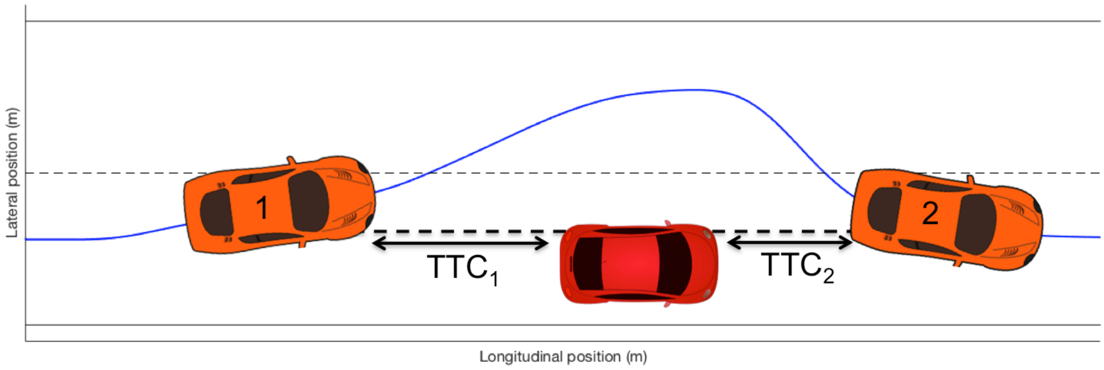

Figure A-1. Time-to-Collision in two parts of the manoeuvre is shown on lateral (m) and longitudinal position (m). The first part (1) entails the ego car taking over the other car and TTC_1 is calculated when the right side of the ego car is at the same lateral position as the left side of the other car. Oppositely, the second part (2) entails the ego car returning to the right lane and TTC_2 is calculated when the right side of the ego car is again at the same lateral position as the left side of the other car.

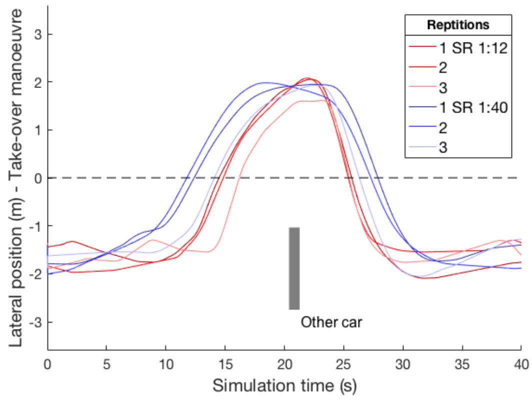

Figure A-1. Typical overtaking trajectories (participant 20) are the lateral positions of ego car in three manoeuvres at each steering ratio 1:12 (red) and 1:40(blue) vs. simulation time (s). At 21.4s the other car is out-of-sight at which the participants are instructed to return to the right lane. Ego car drives at 80km/h and other car at 60km/h.

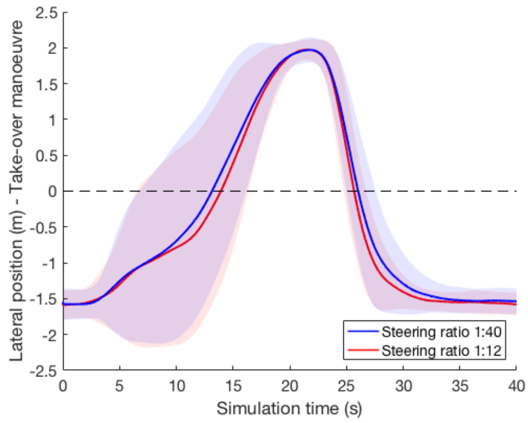

Figure A-2. Mean and standard deviations of overtaking trajectories over all participants are the lateral positions of ego car at each steering ratio 1:12(red) and 1:40(blue) vs. simulation time (s).

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Result

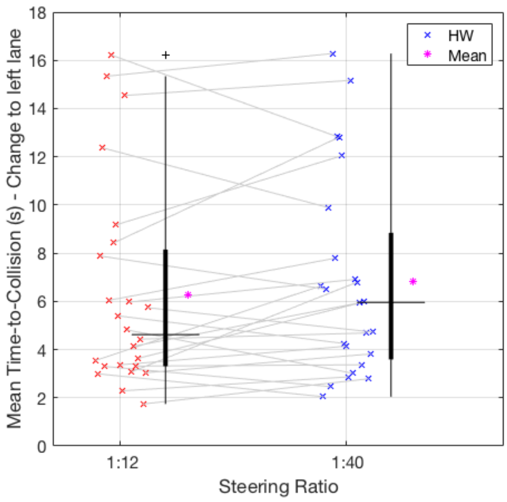


Figure A-3. Mean of Time-to-Collision (part 1) at steering ratio 1:12 (red) and 1:40 (blue). Mean of TTC_1 from three changes to the left lane. No sig. effect is seen (p= 0.2776, d_z=-0.16)

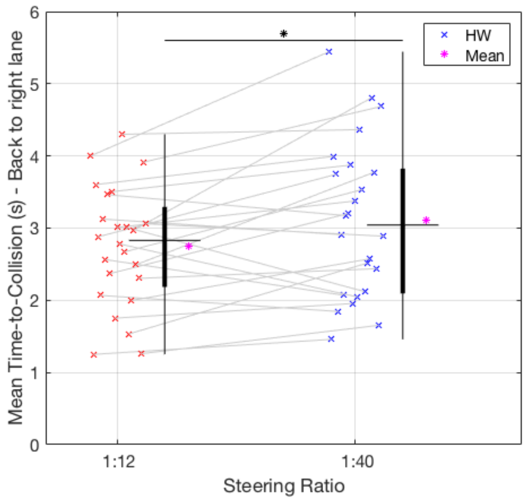


Figure A-4. Mean of Time-to-Collision (part 2) at steering ratio 1:12 (red) and 1:40 (blue). Mean of TTC_2 of three changes back to the right lane. A sig. increase of TTC is seen (p= 0.0258, d_z=-0.32)

The first part of the overtaking manoeuvres did not result in different driving behaviour (Fig A-3). The variability in driver's behaviour seems to be high in the change to the left lane (Fig A-2). However in the manoeuvre back to the right lane (part 2), driver seem to have higher time-to-collision (Fig. A-4). The drivers may steer back lower the right lane with steering ratio 1:40 compared to 1:12.

Appendix

B

Correlations

Table B-1: Correlation matrix Spearman for Country road (CR) – Steering ratio 1:12

CR – 1:12		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.
1. Steering wheel angle	-reversal rate	1.00																	
2.	-root mean squared	**0.53**	1.00																
3. Steering wheel torque	-root mean squared	**0.58**	**0.77**	1.00															
4. Lateral position error	-standard deviation	-0.14	-0.13	-0.12	1.00														
5.	-mean peak-to-peak-time	**-0.68**	**-0.75**	**-0.61**	0.49	1.00													
6. Time-to-lane-crossing	-mean lowest 15-percentile	-0.00	0.10	-0.00	**-0.73**	-0.28	1.00												
7. NASA-TLX	-mean	0.34	0.19	0.35	-0.34	-0.44	0.15	1.00											
8. Acceptance (1) 'I had the vehicle safely under control'		-0.15	-0.37	-0.45	0.33	**0.57**	-0.19	**-0.62**	1.00										
9. (2) 'Control of the vehicle felt realistic'		0.03	0.03	-0.12	0.43	0.22	-0.40	-0.28	0.29	1.00									
10. (3) 'I felt comfortable'		-0.02	0.02	-0.17	0.44	0.25	-0.42	-0.41	0.45	**0.61**	1.00								
11. (4) 'The vehicle responded realistically to steering movements'		0.13	-0.03	-0.31	0.27	0.15	-0.24	-0.37	0.49	0.43	0.49	1.00							
12. (5) 'I found the vehicle easy to control'		0.00	0.10	-0.21	0.25	0.16	-0.20	**-0.66**	**0.52**	**0.68**	0.71	**0.54**	1.00						
13. (6) 'I found the vehicle course stable'		0.09	0.25	0.09	0.28	0.12	-0.25	-0.44	0.44	**0.59**	**0.78**	**0.53**	**0.70**	1.00					
14. (7) 'How soon does the vehicle react after you turn the steering wheel?'		-0.03	-0.36	-0.38	0.33	0.30	-0.18	-0.43	**0.50**	0.20	0.40	0.31	0.40	0.11	1.00				
15. (8) 'How do you like this configuration of the steering overall?'		-0.04	-0.17	-0.36	0.17	0.23	-0.16	**-0.63**	**0.57**	0.49	**0.61**	0.53	0.76	0.49	**0.67**	1.00			
16. DSSQ	-Engagement	-0.18	0.03	-0.06	-0.13	-0.06	0.20	-0.16	-0.04	-0.17	0.07	0.14	0.24	-0.03	0.26	0.17	1.00		
17.	-Distress	0.04	0.22	0.16	-0.05	-0.40	-0.10	0.42	**-0.55**	-0.29	-0.29	0.10	-0.33	-0.26	-0.22	-0.31	0.23	1.00	
18.	-Worry	-0.15	-0.09	-0.13	0.07	0.01	-0.15	0.13	0.10	-0.39	-0.17	0.18	-0.34	-0.19	-0.06	-0.31	0.13	0.46	1.00

Table B-2: Correlation matrix Spearman for Highway (HW) – Steering ratio 1:12

HW – 1:12		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.
1. Steering wheel angle	-reversal rate	1.00																	
2.	-root mean squared	**0.95**	1.00																
3. Steering wheel torque	-root mean squared	**0.89**	**0.88**	1.00															
4. Lateral position error	-standard deviation	-0.02	0.09	-0.14	1.00														
5.	-mean peak-to-peak-time	**-0.78**	**-0.74**	**-0.81**	0.36	1.00													
6. Time-to-lane-crossing	-mean lowest 15-percentile	**-0.92**	**-0.91**	**-0.85**	-0.10	**0.77**	1.00												
7. NASA-TLX	-mean	-0.37	-0.38	-0.36	-0.29	0.18	0.38	1.00											
8. Acceptance (1) 'I had the vehicle safely under control'		0.20	0.27	0.23	0.29	-0.01	-0.13	-0.48	1.00										
9. (2) 'Control of the vehicle felt realistic'		0.33	0.35	0.26	0.41	-0.08	-0.35	-0.23	0.45	1.00									
10. (3) 'I felt comfortable'		0.11	0.13	0.21	0.32	-0.05	-0.09	-0.45	0.36	0.38	1.00								
11. (4) 'The vehicle responded realistically to steering movements'		0.33	0.27	0.30	0.02	-0.29	-0.30	**-0.59**	0.36	**0.54**	**0.59**	1.00							
12. (5) 'I found the vehicle easy to control'		0.30	0.28	0.29	0.27	-0.16	-0.24	-0.41	**0.54**	**0.57**	**0.76**	**0.73**	1.00						
13. (6) 'I found the vehicle course stable'		**0.54**	0.47	**0.50**	0.00	-0.47	**-0.52**	-0.42	0.35	0.43	**0.58**	**0.70**	**0.73**	1.00					
14. (7) 'How soon does the vehicle react after you turn the steering wheel?'		0.26	0.28	0.28	0.40	0.03	-0.12	-0.15	0.40	0.37	0.43	0.13	0.36	0.07	1.00				
15. (8) 'How do you like this configuration of the steering overall?'		0.11	0.05	0.09	0.25	0.02	-0.09	**-0.57**	0.27	0.40	**0.75**	**0.71**	**0.70**	**0.54**	0.22	1.00			
16. DSSQ	-Engagement	-0.01	-0.16	-0.00	-0.34	-0.12	0.14	-0.22	0.02	-0.24	0.23	0.08	0.26	0.18	-0.09	0.25	1.00		
17.	-Distress	-0.24	-0.24	-0.28	-0.11	-0.10	0.11	0.48	**-0.54**	-0.41	-0.39	-0.47	**-0.52**	-0.31	-0.38	-0.40	-0.13	1.00	
18.	-Worry	-0.26	-0.29	-0.24	0.09	0.10	0.14	0.19	0.00	-0.25	-0.30	-0.34	-0.31	-0.17	-0.21	-0.45	-0.07	**0.51**	1.00

Table B-3: Correlation matrix Spearman for Country road (CR) – Steering ratio 1:40

CR – 1:40		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.
1. Steering wheel angle	-reversal rate	1.00																	
2.	-root mean squared	0.27	1.00																
3. Steering wheel torque	-root mean squared	**0.80**	0.49	1.00															
4. Lateral position error	-standard deviation	**-0.50**	0.12	**-0.54**	1.00														
5.	-mean peak-to-peak-time	-0.49	**-0.67**	**-0.65**	0.49	1.00													
6. Time-to-lane-crossing	-mean lowest 15-percentile	0.09	-0.02	0.27	**-0.75**	-0.42	1.00												
7. NASA-TLX	-mean	0.38	0.43	0.36	-0.20	-0.44	0.13	1.00											
8. Acceptance (1) 'I had the vehicle safely under control'		-0.14	-0.34	-0.09	0.10	0.39	-0.04	**-0.63**	1.00										
9. (2) 'Control of the vehicle felt realistic'		-0.24	-0.38	-0.15	-0.12	0.16	0.21	-0.29	**0.67**	1.00									
10. (3) 'I felt comfortable'		-0.10	-0.26	-0.03	-0.15	0.14	0.22	**-0.59**	**0.78**	**0.74**	1.00								
11. (4) 'The vehicle responded realistically to steering movements'		-0.06	-0.36	-0.10	-0.11	0.08	0.14	-0.22	**0.56**	**0.87**	**0.68**	1.00							
12. (5) 'I found the vehicle easy to control'		-0.11	-0.11	0.06	-0.11	-0.04	0.18	-0.47	**0.77**	**0.73**	**0.79**	**0.66**	1.00						
13. (6) 'I found the vehicle course stable'		-0.12	-0.20	0.07	-0.34	-0.02	0.46	-0.21	**0.56**	**0.50**	**0.53**	0.42	**0.55**	1.00					
14. (7) 'How soon does the vehicle react after you turn the steering wheel?'		-0.06	-0.25	0.15	-0.41	-0.19	0.30	-0.12	0.31	0.41	0.19	0.44	0.49	**0.52**	1.00				
15. (8) 'How do you like this configuration of the steering overall?'		-0.27	**-0.50**	-0.35	-0.05	0.26	0.13	-0.36	**0.66**	**0.84**	**0.70**	**0.79**	**0.71**	0.42	0.35	1.00			
16. DSSQ	-Engagement	-0.35	0.10	-0.09	-0.13	-0.24	0.31	0.00	-0.01	0.36	0.16	0.22	0.19	0.17	0.06	0.22	1.00		
17.	-Distress	0.19	0.46	0.17	0.03	-0.42	-0.12	**0.72**	**-0.66**	-0.36	**-0.66**	-0.38	-0.45	-0.42	-0.13	-0.42	0.03	1.00	
18.	-Worry	-0.29	-0.15	-0.38	0.26	0.04	-0.35	0.01	-0.06	0.12	-0.19	0.00	0.01	-0.32	0.16	0.23	0.17	0.22	1.00

Table B-4: Correlation matrix Spearman for Highway (HW) – Steering ratio 1:40

HW – 1:40		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.
1. Steering wheel angle	-reversal rate	1.00																	
2.	-root mean squared	**0.95**	1.00																
3. Steering wheel torque	-root mean squared	**0.89**	**0.93**	1.00															
4. Lateral position error	-standard deviation	-0.32	-0.16	-0.18	1.00														
5.	-mean peak-to-peak-time	**-0.90**	**-0.86**	**-0.85**	0.48	1.00													
6. Time-to-lane-crossing	-mean lowest 15-percentile	**-0.72**	**-0.79**	**-0.68**	-0.16	**0.54**	1.00												
7. NASA-TLX	-mean	0.07	0.08	0.10	-0.20	-0.15	0.20	1.00											
8. Acceptance (1) 'I had the vehicle safely under control'		0.02	-0.01	-0.03	-0.27	-0.06	0.07	-0.26	1.00										
9. (2) 'Control of the vehicle felt realistic'		0.23	0.17	0.19	-0.05	-0.00	-0.10	-0.14	**0.53**	1.00									
10. (3) 'I felt comfortable'		-0.01	0.02	0.14	0.24	0.00	0.04	-0.31	0.03	0.21	1.00								
11. (4) 'The vehicle responded realistically to steering movements'		0.22	0.25	0.14	-0.00	-0.00	-0.14	-0.14	0.19	**0.54**	0.24	1.00							
12. (5) 'I found the vehicle easy to control'		0.23	0.13	0.21	-0.10	-0.08	-0.12	-0.46	0.19	**0.54**	**0.57**	0.30	1.00						
13. (6) 'I found the vehicle course stable'		0.22	0.10	0.18	0.01	-0.10	-0.09	-0.45	0.15	0.46	**0.60**	0.27	**0.84**	1.00					
14. (7) 'How soon does the vehicle react after you turn the steering wheel?'		0.24	0.27	0.16	-0.27	-0.11	-0.05	0.40	0.16	0.44	-0.09	**0.58**	0.15	-0.04	1.00				
15. (8) 'How do you like this configuration of the steering overall?'		0.02	0.00	0.11	-0.23	0.08	0.16	0.08	0.09	**0.50**	0.32	0.28	0.46	0.41	0.36	1.00			
16. DSSQ	-Engagement	0.06	0.06	0.16	-0.41	-0.24	0.20	0.40	-0.20	-0.27	0.13	-0.08	-0.21	-0.10	0.08	0.21	1.00		
17.	-Distress	0.32	0.30	0.14	-0.00	-0.16	-0.35	0.39	-0.43	-0.08	-0.44	0.09	-0.38	-0.29	0.15	-0.13	-0.01	1.00	
18.	-Worry	-0.10	0.01	-0.14	0.10	-0.06	0.02	0.06	0.05	-0.32	-0.10	-0.17	-0.31	-0.31	-0.10	-0.23	-0.09	0.17	1.00

Appendix

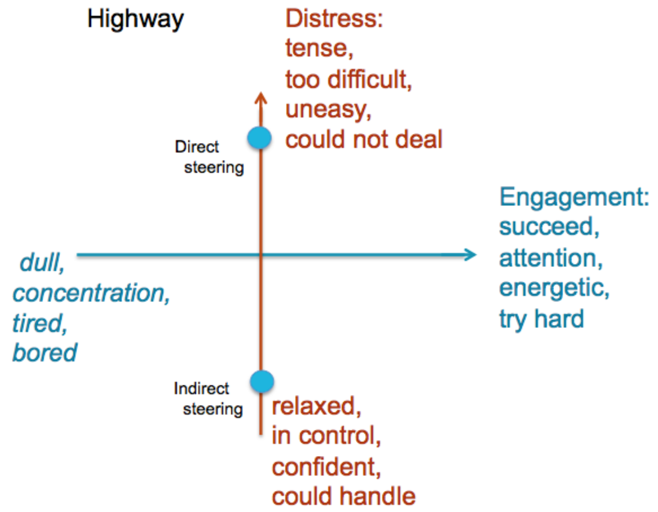
C

Results

Results

Dundee 3-State Stress test

Hypothesis



The expectation is that steering ratio 1:12 amplifies engagement and activation of the driver.
Steering ratio 1:40 results a higher workload for the driver. That is expected to raise distress in a high steering demand environment.

On contrary in a low steering demand environment a direct steering is expected to cause distress.
Steering ratio 1:40 is expected to actually relax the driver, because it takes less effort to track a lane accurately.

Results

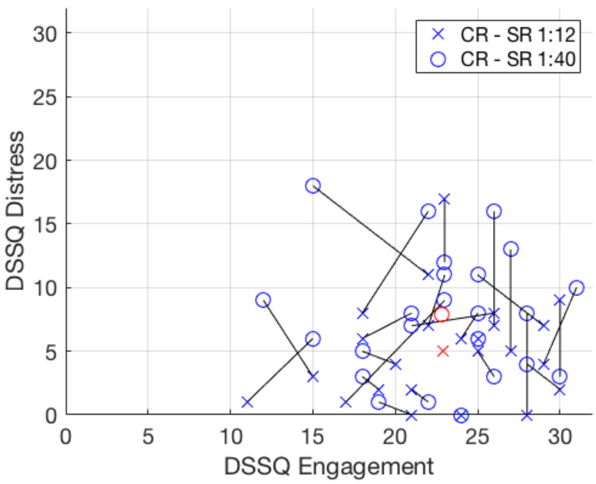


Figure C-1a. Distress and Engagement on country road (CR)

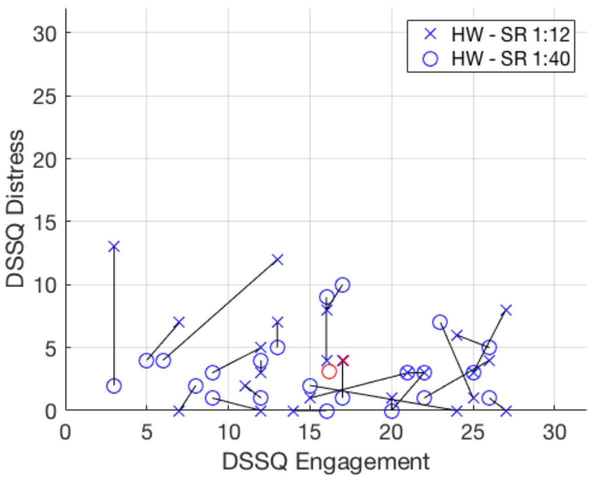


Figure C-1b. Distress and Engagement on highway (HW)

Figure C-1. Distress and Engagement are both measured with 8 questions from the short Dundee Stress 3-State Questionnaire for two steering ratios 1:40 and 1:12. Red is the mean of the correspondent data. Score 32 means maximally distressed. Score 32 means maximally engaged.

DSSQ – Worries

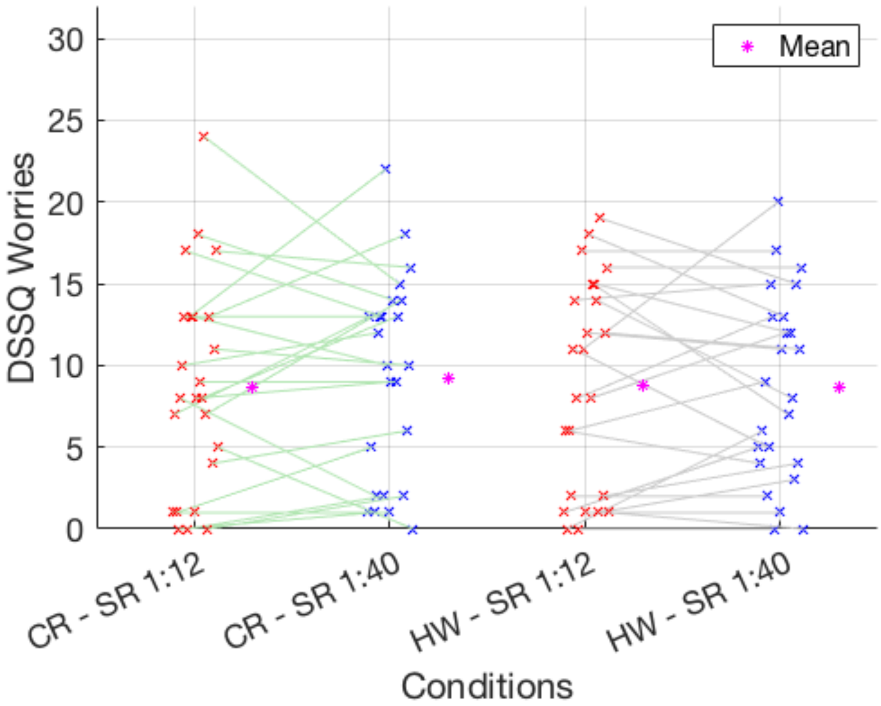


Figure C-2. Worries are measured with 8 questions from the short Dundee Stress 3-State Questionnaire for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black). Score 32 means maximally worried.

Conclusion

The DSSQ seem inconclusive with this experiment data. However at CR steering ratio 1:40 leads to increased distress.

Acceptance questionnaire

Hypothesis	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Acceptance	🡅	🡇	**Acceptance**	🡇	🡅

Acceptance is expected to be higher for 1:12 than 1:40 in this condition, because workload might be lower and safety might be higher.

In this environment the Acceptance is expected to be higher for steering ratio 1:40, because of higher performance (lateral position) and less corrections.

Results

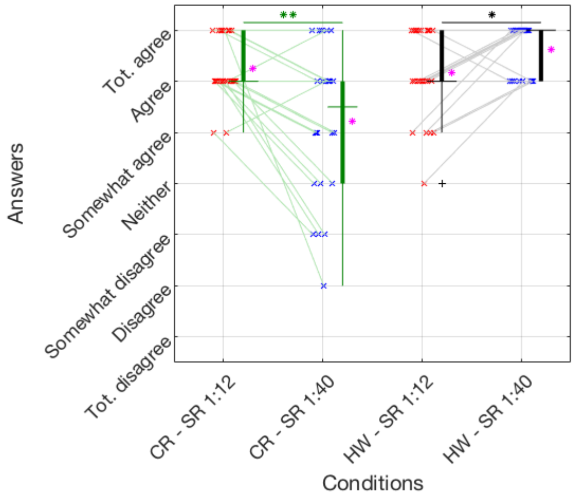


Figure C-3a. Question 1 'I had the vehicle safely under control.'
Both results are according to hypothesis.

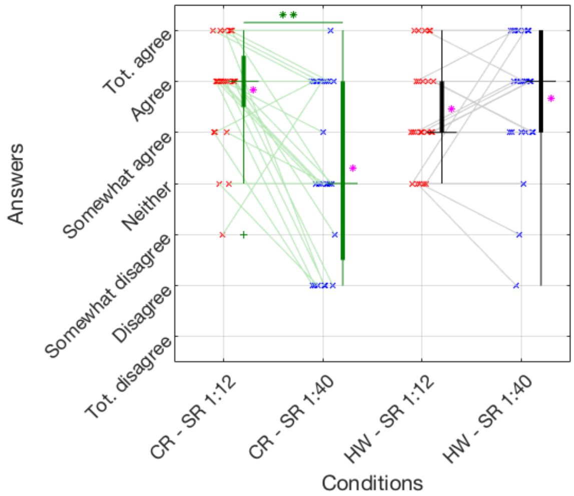


Figure C-3b. Question 2 'The control of the vehicle felt realistic.'
Only the result on the country road (CR) is according to hypothesis.

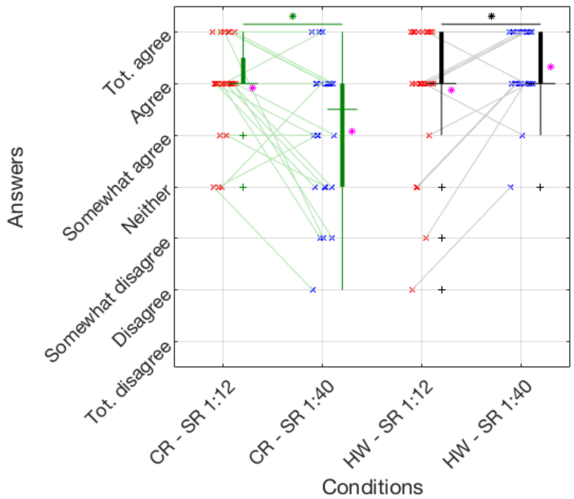


Figure C-3c. Question 3 'I felt comfortable.'
Both results are according to hypothesis.

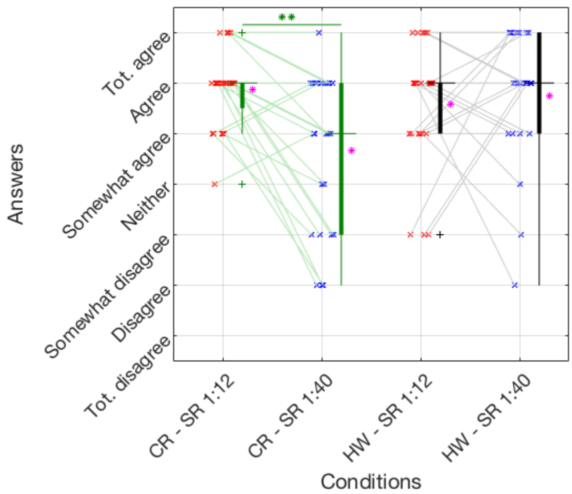


Figure C-3d. Question 4 'The vehicle responded realistically to steering movements.'
Only the result on the country road (CR) is according to hypothesis.

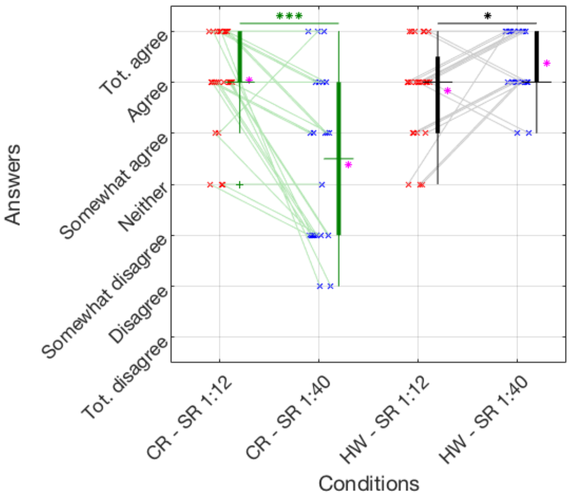


Figure C-3e. Question 5 'I found the vehicle easy to control.' Both results are according to hypothesis.

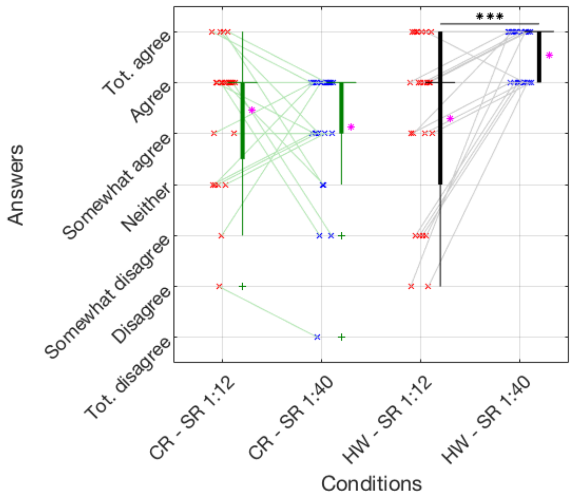


Figure C-3f. Question 6 'I found the vehicle course stable.' Only the result on the country road is according to hypothesis.

Figure C-3. Statements are from self-reported acceptance questionnaire for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
* significance level of p<0.05, ** p<0.01, *** p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

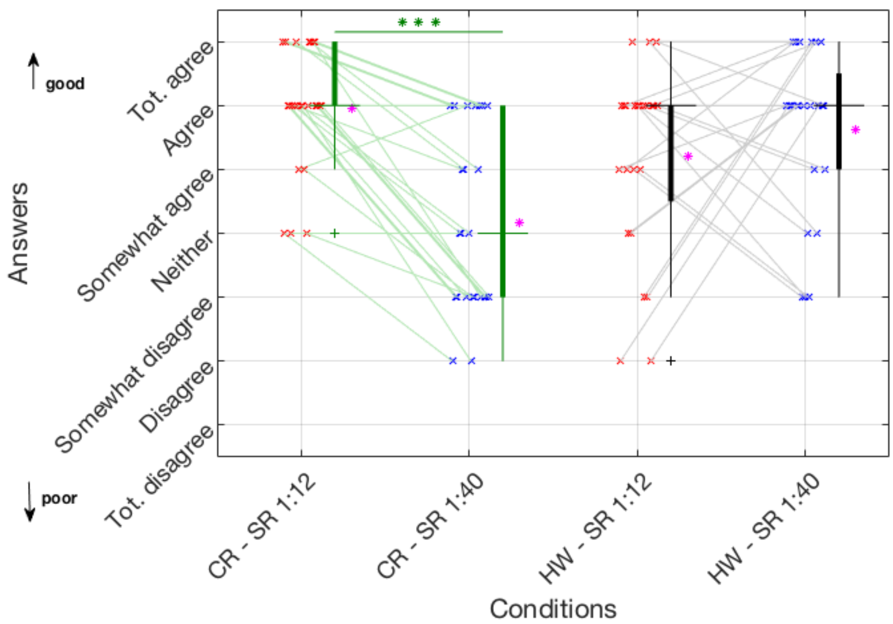


Figure C-4. Overall steering rating question 8 'How do you like this configuration of the steering overall?' from self-reported acceptance questionnaire for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black). *** significance level of p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Conclusion

Results are similar the hypothesis for CR, except for question 6. For HW the results are similar to as the hypothesis as well, except for the questions 2 and 4.

Acceptance questionnaire – *Vehicle delay behaviour (7)*

Hypothesis	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Delay	🡅	🡇	TLC	🡅	🡇

Dependent variable:
1:12 steering ratio is more direct and could decrease delays noticeably compared to a steering ratio of 1:40.

Even in small steering wheel angles the vehicle reaction with a ratio of 1:12 is noticeably slower than 1:40.

Results

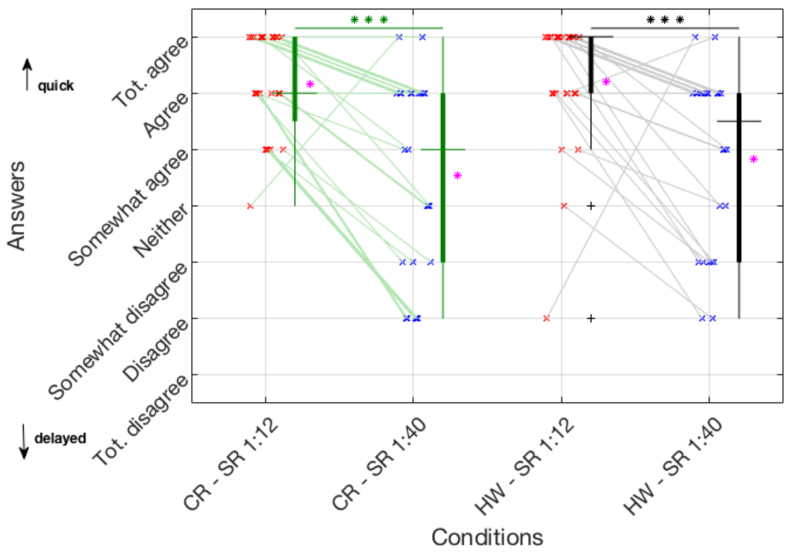


Figure C-5. Vehicle response delay rating question 7 'How soon does the vehicle react after you turn the steering wheel?' from self-reported acceptance questionnaire for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black). *** significance level of p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Conclusion

Participants did notice the delay of the vehicle steering for both road types.

NASA-TLX workload questionnaire

Hypothesis	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
NASA-TLX	↓	↑	NASA-TLX	↑	↓

Much higher angles in CR lead to much higher steering wheel angles and torques, directly related to workload experience.

The experienced workload is expected to be lower with steering ratio 1:40, because steering accuracy is more important to this task than steering rate and torques.

Results

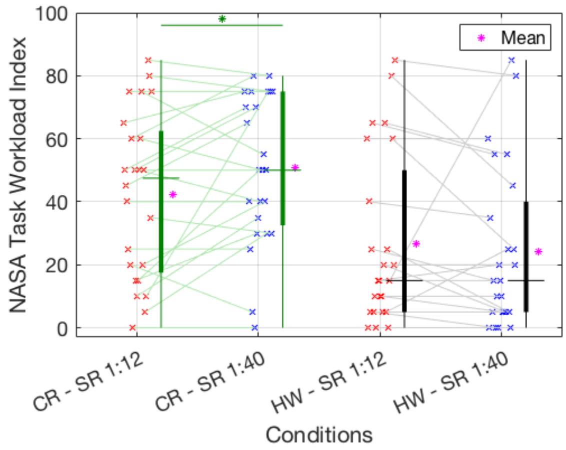


Figure C-6a. Mental demand from NASA-TLX questionnaire
Only the result on the country road (CR) is according to hypothesis.

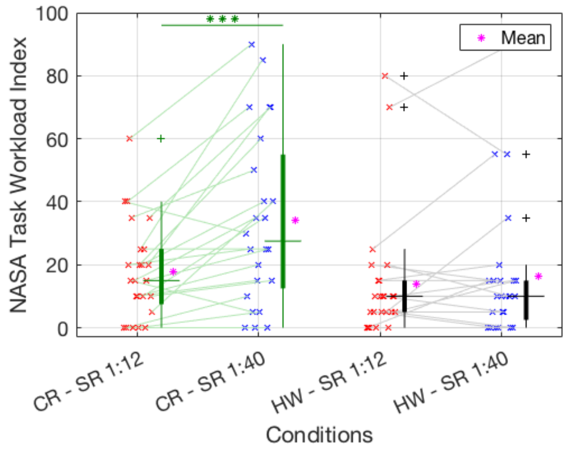


Figure C-6b. Physical demand from NASA-TLX questionnaire
Only the result on the country road (CR) is according to hypothesis.

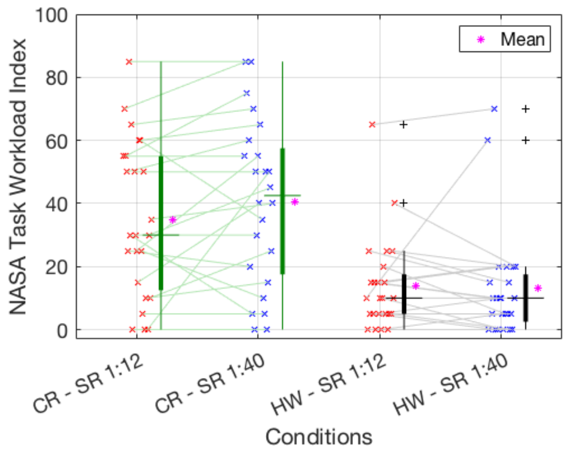


Figure C-6c. Temporal demand from NASA-TLX questionnaire
Results from both country road (CR) and highway (HW) are inconclusive

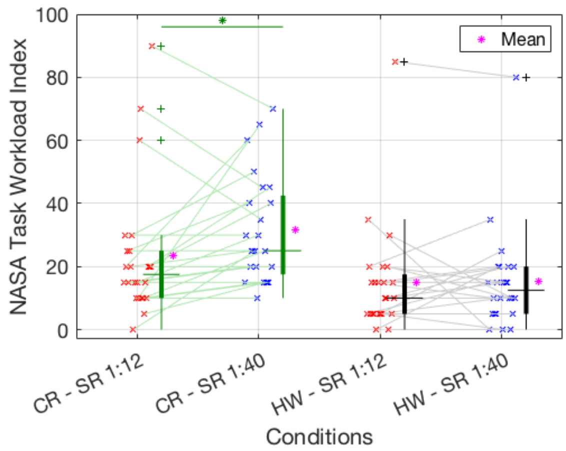


Figure C-6d. Performance from NASA-TLX questionnaire
Only the result on the country road (CR) is according to hypothesis.

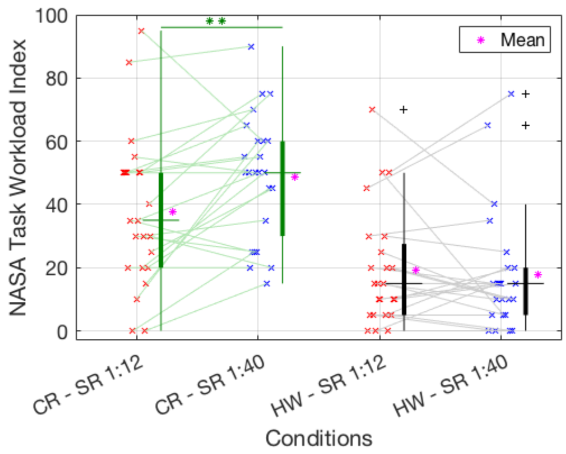


Figure C-6e. Effort from NASA-TLX questionnaire Only the result on the country road (CR) is according to hypothesis.

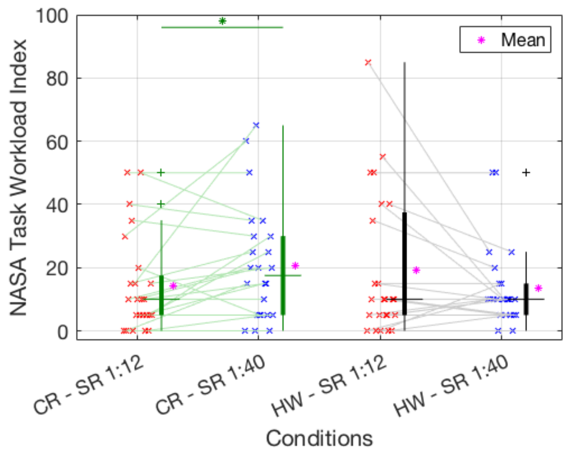


Figure C-6f. Frustration from NASA-TLX questionnaire Only the result on the country road (CR) is according to hypothesis.

Figure C-6. Answers of NASA-TLX questionnaire for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
* significance level of p<0.05, ** p<0.01, *** p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

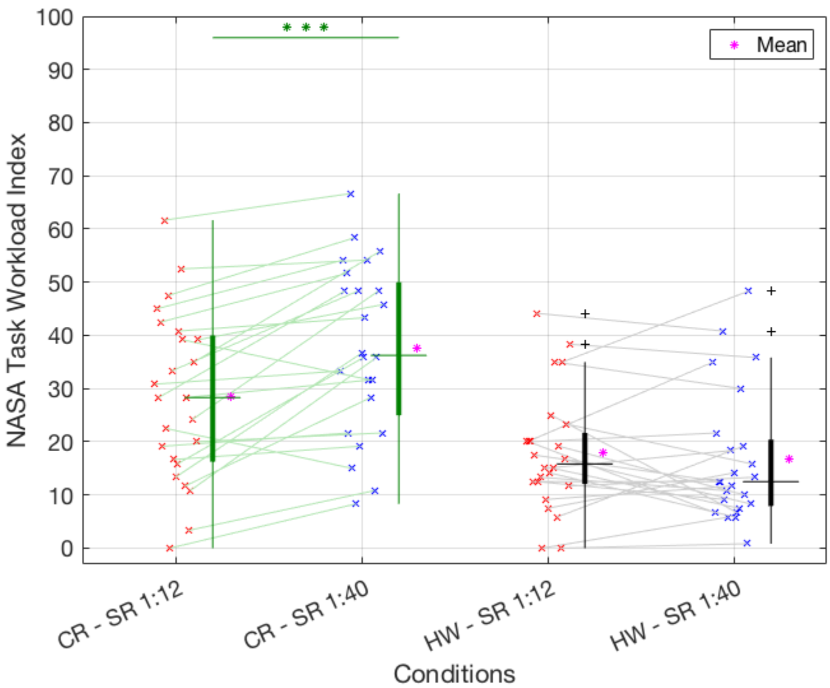


Figure C-7. Mean of mental, physical and temporal demand, performance, effort and frustration answers of NASA-TLX questionnaire for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
*** significance level of p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Conclusion

The 'task workload index' seems a lower for steering ratio 1:12 compared to steering ratio 1:40 in the CR condition. For highway environment this metric is rather inconclusive with this data.

RMSE of steering wheel torque

Hypothesis	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Tsw	↓	↑	Tsw	-	-

Much higher angles in CR lead to much higher torques; directly related to steering ratio and steering wheel stiffness.

Steering wheel angle is expected to be so small that torque differences are not significant.

Results

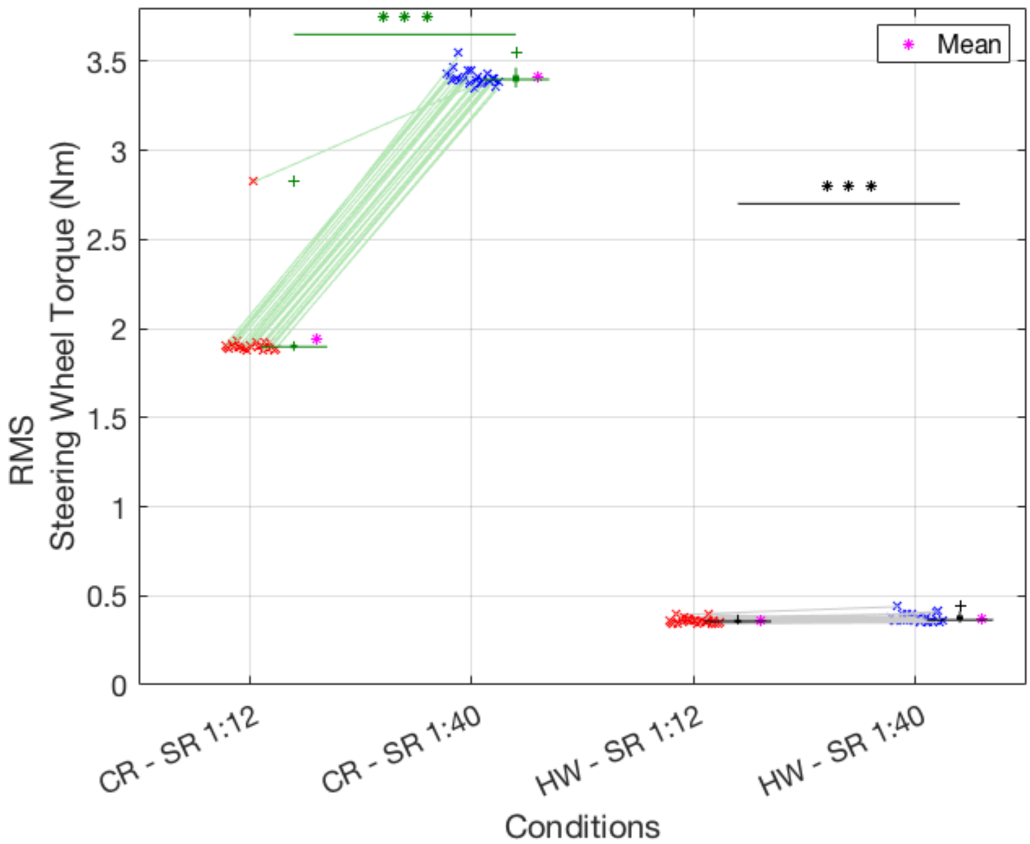


Figure C-8. Root mean square of steering wheel torque (Nm) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
*** significance level of p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.
Note that an error appeared in the stiffness function in CR at steering ratio 1:12 at participant 14. That results in more steering wheel torque (RMS=2.824Nm) than the rest and is marked by the boxplot as an outlier. And is also noticeable in Steering wheel torque distribution (Appendix D - Vehicle).

Conclusion
In both environments the difference in torque input of the driver on the steering wheel is significantly higher for steering ratio 1:40. Interestingly, the (mean) difference is only a very small, 0.0151 Nm. The mean is 0.3591(std 0. 0149) for 1:12 and 0.3742 (std 0.0223) for 1:40.

Steering wheel angle - Reversal Rate

Hypothesis	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
SRR	↓	↑	***SRR***	↑	↓

Corrections on CR have to be performed quickly. Steering ratio 1:40 demands higher steering rate, which results in more overshoot and corrections.

Corrections on the highway are much smaller, so overshoot and corrections at steering ratio 1:12 is more likely.

Results

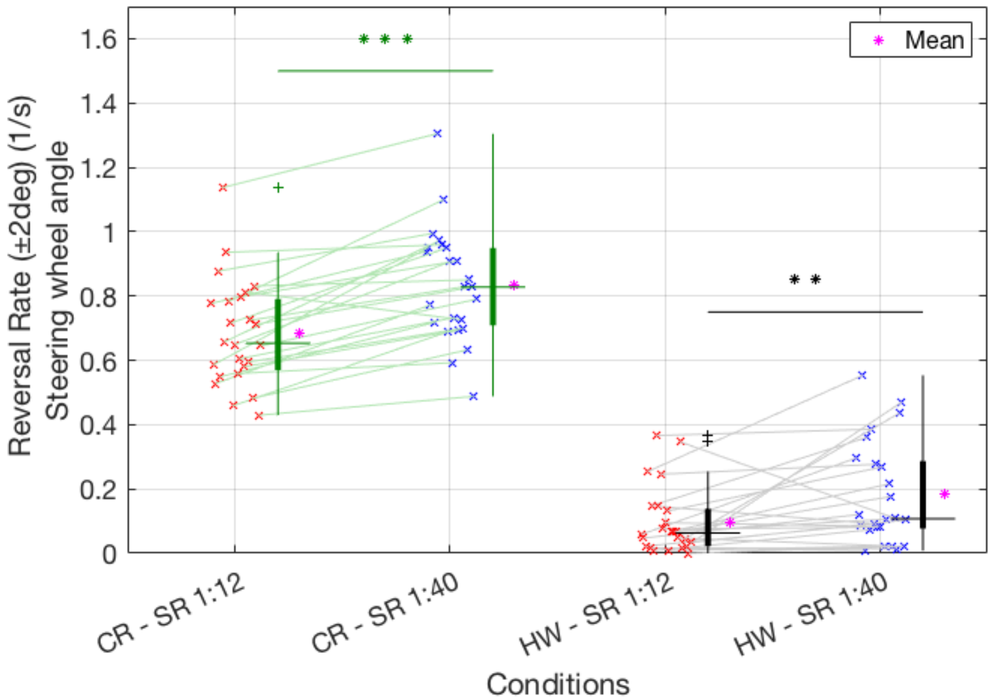


Figure C-9. Reversal Rate (±2deg) of steering wheel angle (1/s) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
* significance level of p<0.05, ** p<0.01, *** p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Conclusion

Unlike the hypothesis, it seems like steering ratio 1:40 causes more reversals in both environments.

Steering wheel angle – RMSE

No hypothesis noted for this condition

Results

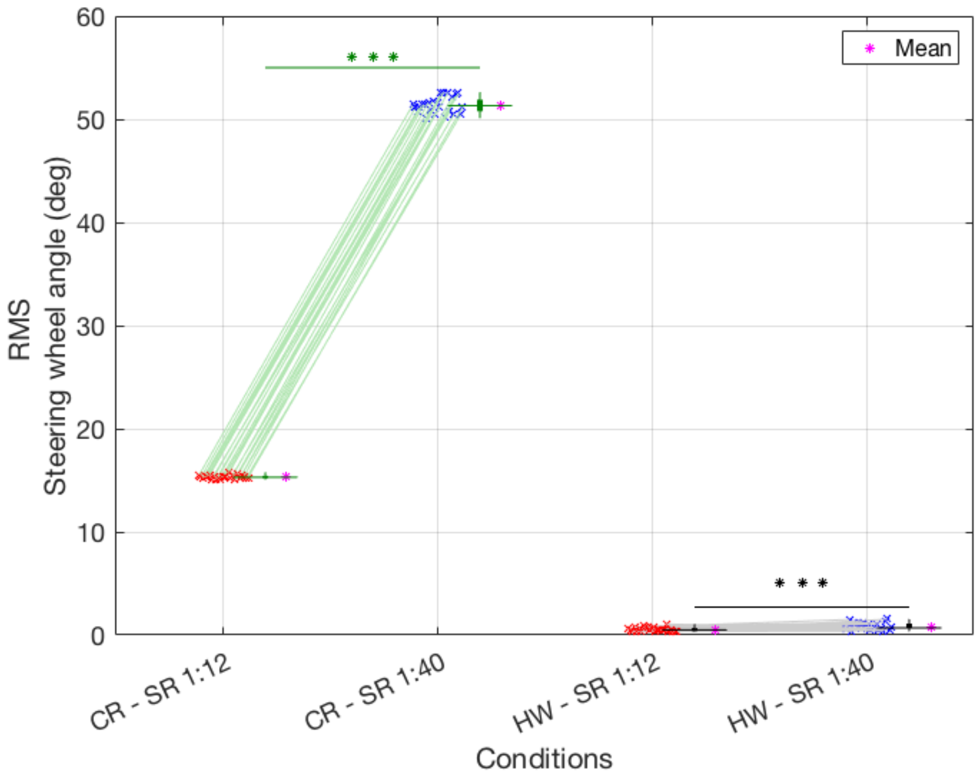


Figure C-10. Root mean square of steering wheel angle (deg) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
* significance level of p<0.05, ** p<0.01, *** p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Standard deviation of lateral position

Hypothesis	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
SDLP	-	-	***SDLP***	🡅	🡇
Drivers cut the curves of the country road. Steering characteristics are not expected to have influence on the amount of curve cutting.			This metric should indicate swerving within the lane for the Highway condition, which is expected to be higher for steering ratio 1:12.		

Results

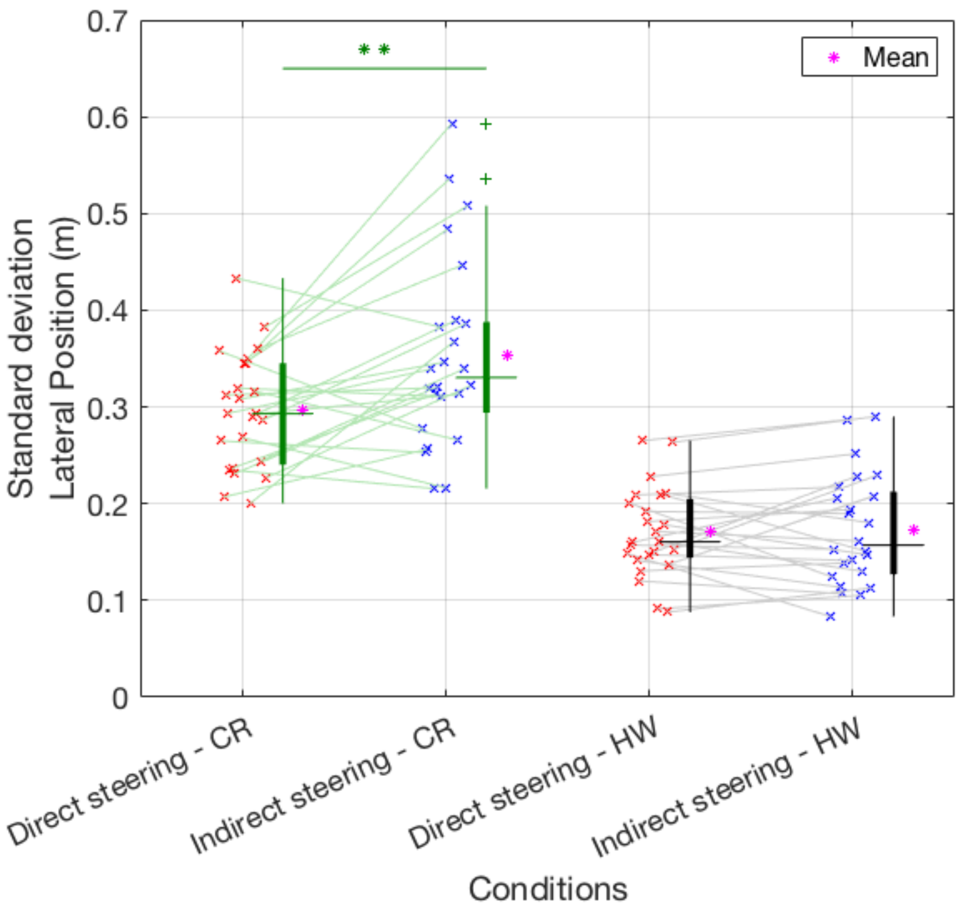


Figure C-11. Standard deviation of lateral position (m) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
** significance level p<0.01. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Conclusion
This seems to be opposite to the expectations for CR; significantly less deviation in road following for steering ratio 1:12. No effect on SDLP is shown for HW.

Average over all participants
Mean and standard deviation of lateral position

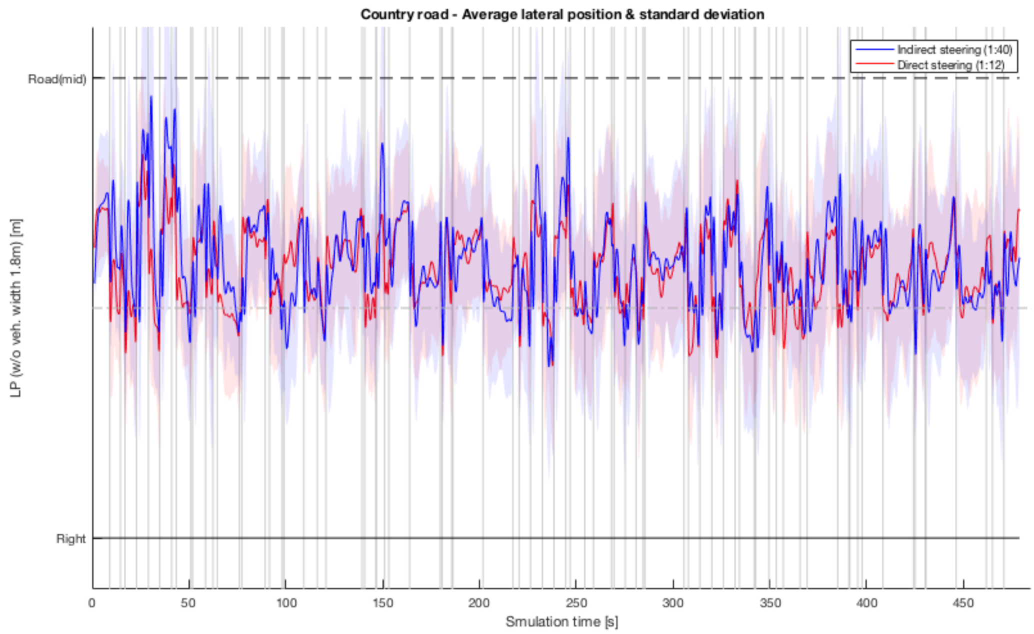


Figure C-12. Mean (line) and standard deviation (colored area) of lateral position of averaged over all participants for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR).

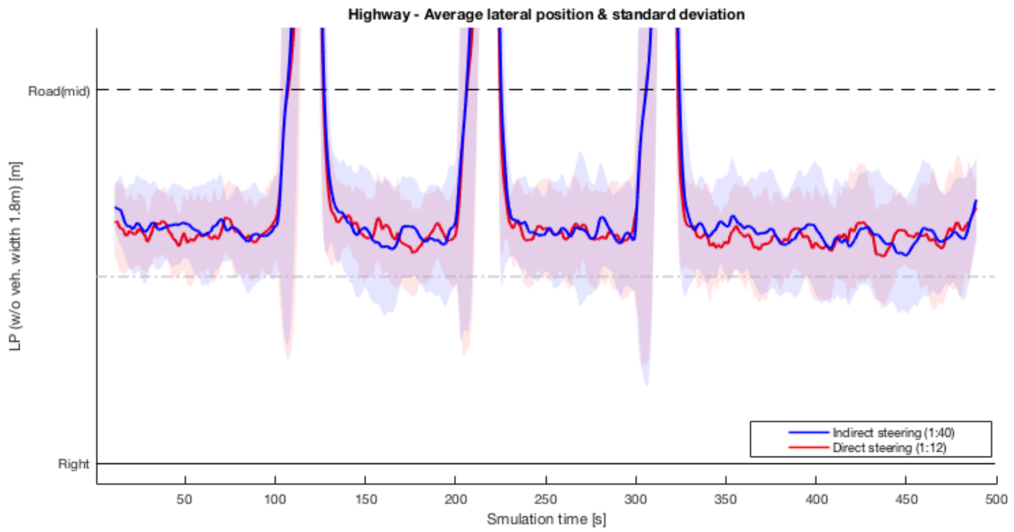


Figure C-13. Mean (line) and standard deviation (colored area) of lateral position of averaged over all participants for two steering ratios 1:12 (red) and 1:40 (blue) on highway (HW).

Count of lateral position peaks

No hypothesis noted for this condition

Results

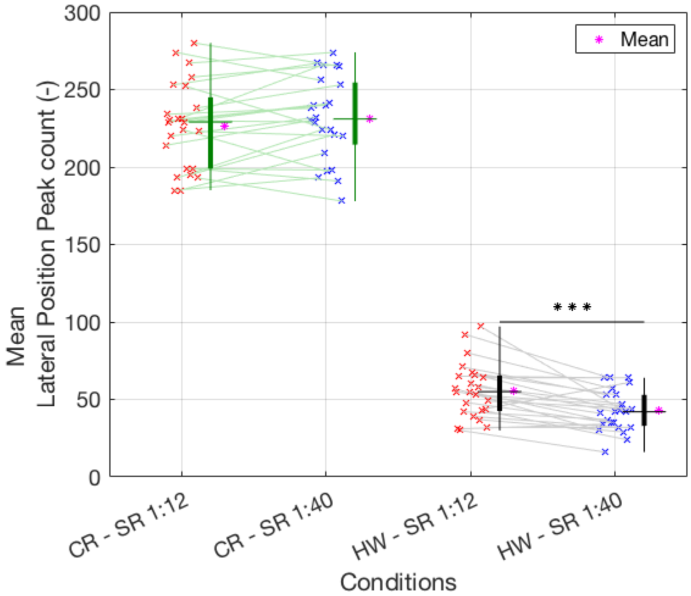


Figure C-14. Mean of lateral position peak count (-) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black). Less peaks are counted for steering ratio 1:40 on HW. *** significance level p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

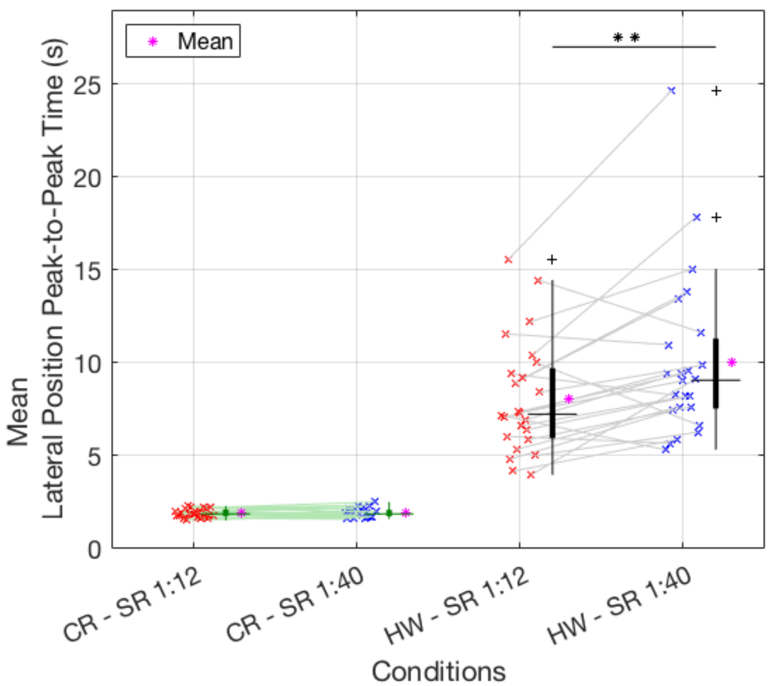


Figure C-14. Mean of lateral position peak-to-peak-time (-) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black). Higher peak-to-peak time is displayed for steering ratio 1:40 on HW. ** significance level p<0.01. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Mean of lowest 15%-tile of time to lane crossing (TLC),

Hypothesis	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
TLC	🡅	🡇	TLC	-	-
	Due to the high steering rate demand in this task, is TLC expected to be higher with direct steering and lower with indirect steering, because the driver is not expected to compensate the steering rate in this setting.		In this environment the TLC is expected to not differ significantly, because the road is thought to be wide enough to have impact on safety		

Results

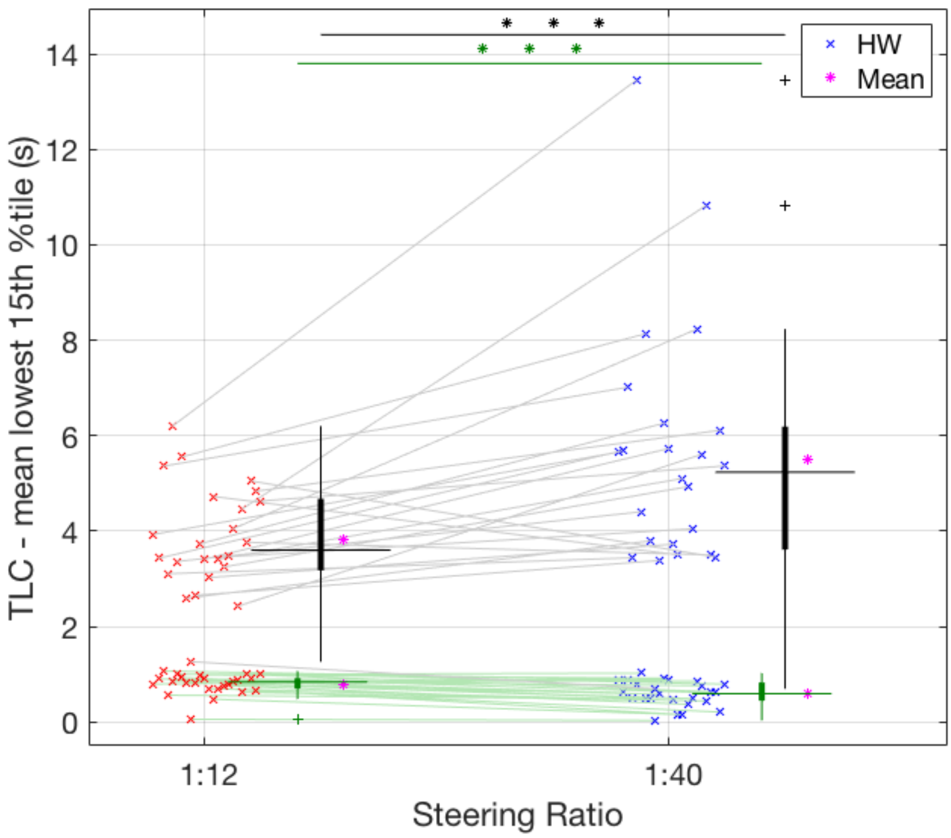


Figure C-15. Mean of lowest 15-percentile of Time-to-line-crossing (TLC) (s) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
* significance level of p<0.05, ** p<0.01, *** p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Conclusion

The mean of the (lowest 15%-tile of) TLC seems to have hypothesized trend for the CR. Interestingly, for HW the steering ratio 1:40 has a higher TLC.

RMSE of Lateral Acceleration
Notice that the participant does not feel lateral acceleration, so there is no feedback loop. The displayed lateral accelerations are from the vehicle model in the simulator.

Hypothesis	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Lat. Acc.	-	-	**Lat. Acc.**	🡅	🡇

Lateral acceleration in CR are expected to not differ significantly.

The lateral accelerations are expected to be higher with steering ratio 1:12 (higher gain). Lateral accelerations can decrease comfort. (Although the participant does not feel this acceleration and does not take action to decrease it.)

Results

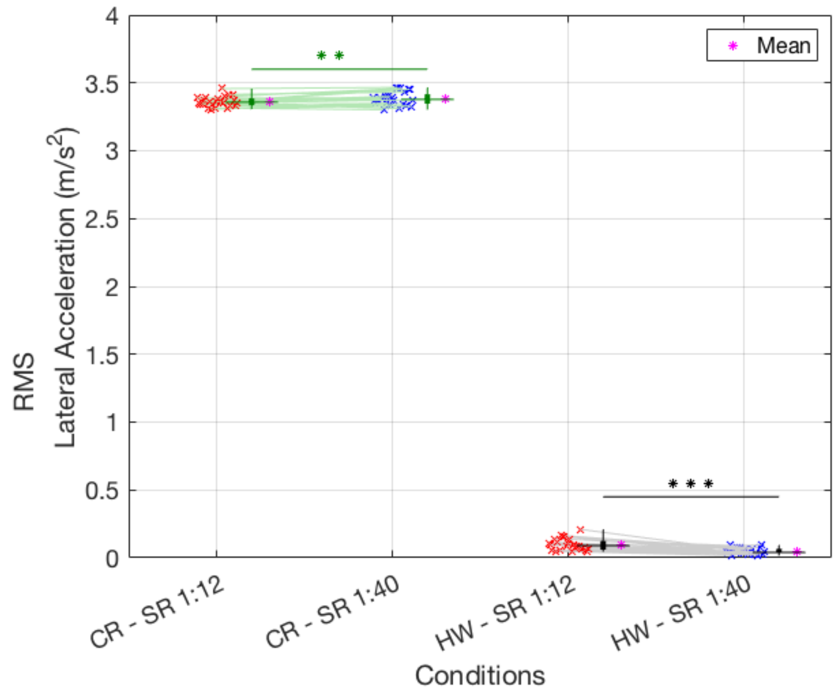


Figure C-16. Root mean square of lateral acceleration (m/s^2) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black).
* significance level of p<0.05, ** p<0.01, *** p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Conclusion

In CR the RMSE value of the lateral acceleration is higher for steering ratio 1:40 compared to 1:12. For HW it seems that the RMSE value of the lateral acceleration is higher for steering ratio 1:12, according to hypothesis.

RMS of yaw rate

Notice that the participant does not feel yaw rate, but only sees the displacement of the virtual environment moving on the screen in the simulator. The displayed yaw rate is from the vehicle model in the simulator.

No hypothesis noted for this condition

Results

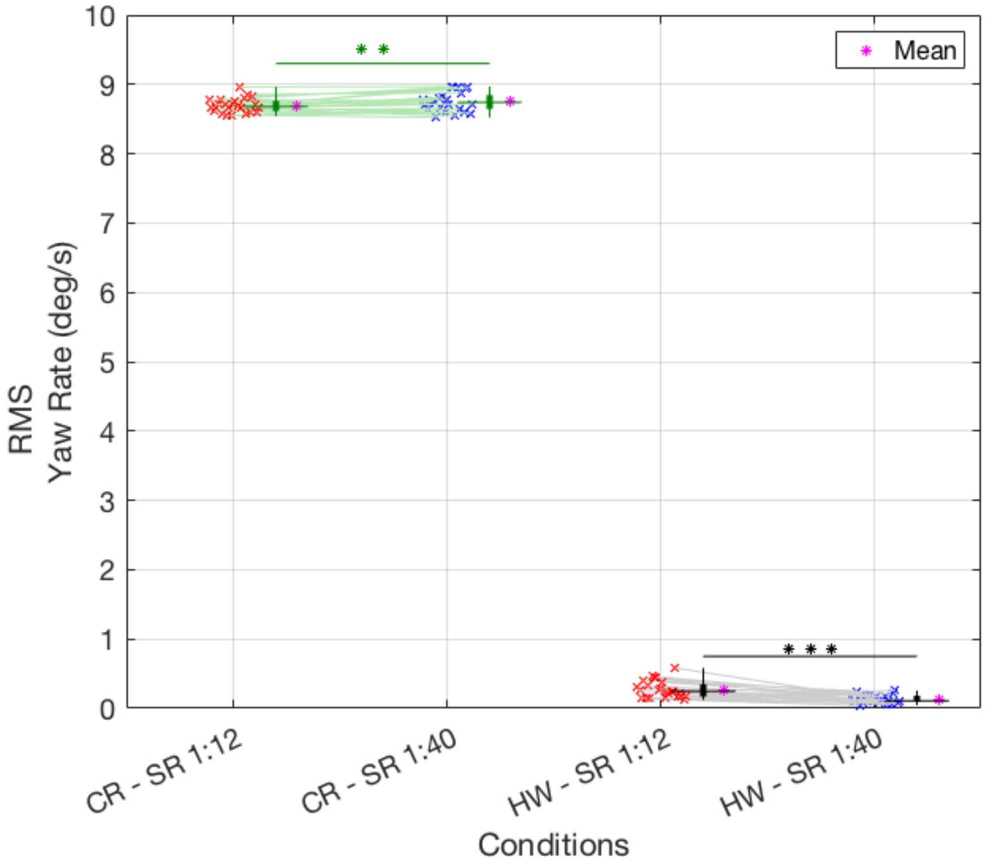


Figure C-17. Root mean square of yaw rate (deg/s) for two steering ratios 1:12 (red) and 1:40 (blue) on country road (CR, green) and highway (HW, black). Higher yaw rate is shown for steering ratio 1:40 on CR. Lower yaw rate is displayed for steering ratio 1:40 on HW. * significance level of p<0.05, ** p<0.01, *** p<0.001. Boxplot of median, 25-percentile and 75-percentile, the magenta asterisk * is the mean.

Nausea rating

No hypothesis noted for this condition

Results

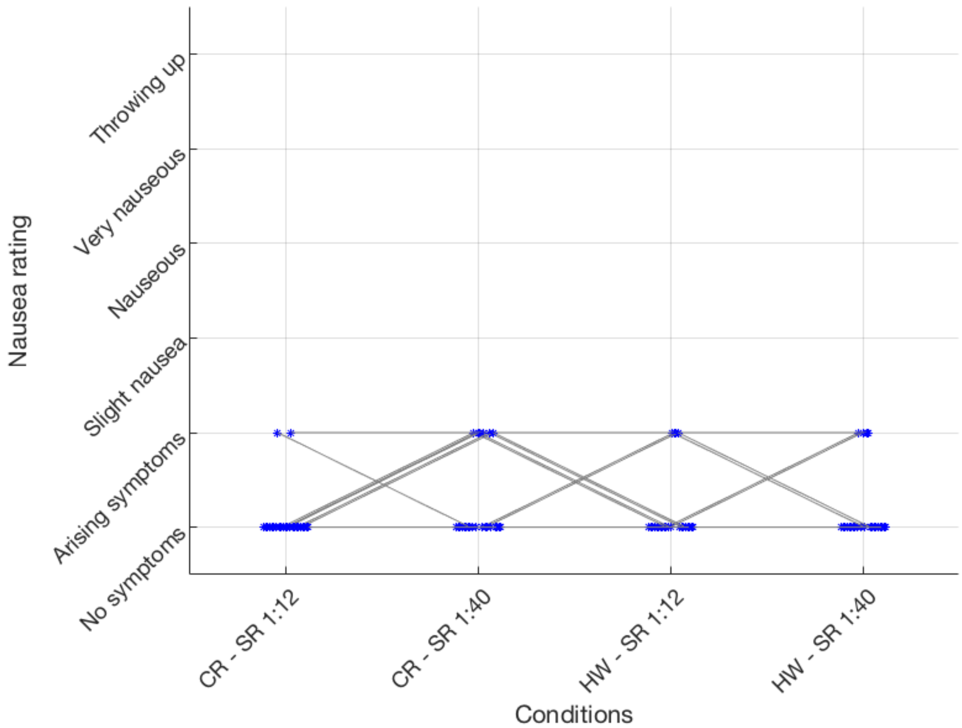


Figure C-17. Nausea questionnaire subjective rating

✔ = experiment data seems to show hypothesized trend
◆= seems to be inconclusive from this experiment data
✖ = experiment data does not show hypothesized trend
! = experiment data seems to show a trend although none hypothesized

DSSQ
CR: ✖ (rather activation then pleasantness)
HW: ✖ (rather opposite: direct more pleasant than indirect)

Acceptance questionnaire

	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Hypothesis	↑	↓		↓	↑
Acceptance			**Acceptance**		
1	↑	↓	**1**	↓	↑
2	↑	↓	**2**	-	-
3	↑	↓	**3**	↓	↑
4	↑	↓	**4**	-	-
5	↑	↓	**5**	↓	↑
6	-	-	**6**	↓	↑
7	↑	↓	**7**	↑ !	↓ !
8	↑	↓	**8**	-	-

NASA-TLX mean

	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Hypothesis	↓	↑		↑	↓
NASA-TLX	↓	↑	NASA-TLX	-	-
result	✔			✖	

Conclusion

✔ = experiment data seems to show hypothesized trend
◆= seems to be inconclusive from this experiment data
✖ = experiment data does not show hypothesized trend
! = experiment data seems to show a trend although none hypothesized

SRR: SW Angle Reversal Rate

	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Hypothesis	↓	↑		↑	↓
SRR	↓	↑	***SRR***	↓	↑
result	✔			✖	

SW Torque RMSE

	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Hypothesis	↓	↑	Tsw	-	-
Tsw	↓	↑		↓	↑
result	✔			!	

SDLP

	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Hypothesis	-	-		↑	↓
SDLP	↓	↑	***SDLP***	-	-
result	!			u	

Time to lane crossing (TLC) Lowest 15 percentile

	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Hypothesis	↑	↓		-	-
TLC	↑	↓	TLC	↓	↑
result	✔			!	

RMSE Lateral Acceleration

	CR – 1:12	CR – 1:40		HW – 1:12	HW – 1:40
Hypothesis	-	-		↑	↓
Lat. Acc.	↓	↑	**Lat. Acc.**	↑	↓
result	!			✔	

Appendix

D

Vehicle

Steering
Design of feedback torque

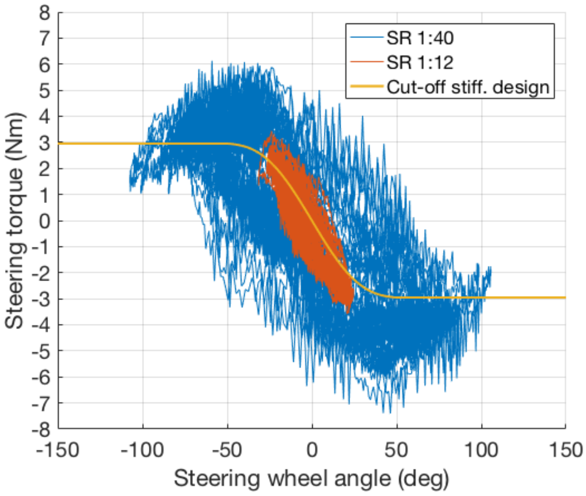


Figure D-1. Typical steering example (participant 18) of steering wheel torque (Nm) (i.e. simulated self-alignment torque) vs. steering wheel angle (deg) plots steering ratio 1:40 (blue) and 1:12 (red). Steering wheel stiffness is designed with a cut-off at 3Nm (yellow) to avoid high unrealistic high torques for SWA above 50deg (Figure 2).

Steering wheel torque distribution

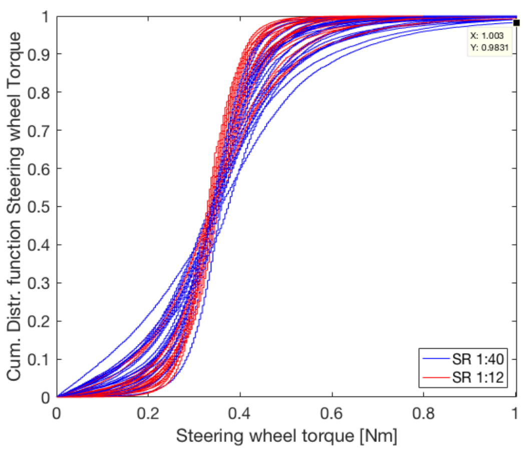


Figure D-2a. Highway (HW)
Both steering ratio 1:40 and 1:12 have 98% of the distribution below 1Nm.

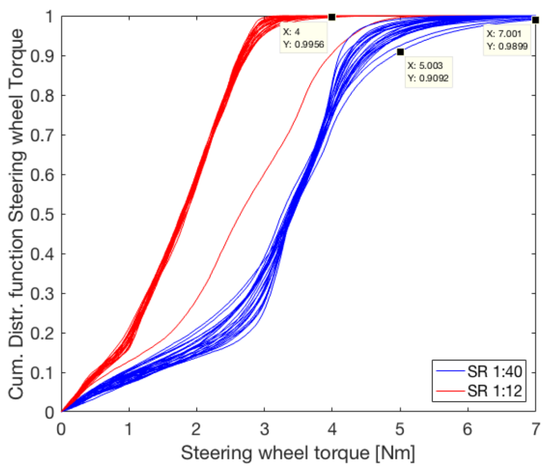


Figure D-2b.
Steering ratio 1:40 (blue) has 99% of the distribution below 7Nm (90% below 5Nm).
Steering ratio 1:12 (red) has 99% of the distribution below 4Nm. (*)

Figure D-2. Steering wheel torque distribution average over all participants in 'cumulated distribution function of steering wheel torque' (Nm) vs. steering wheel torque (Nm) (i.e. simulated self-alignment torque) plots steering ratio 1:40 (blue) and 1:12 (red).
(*) Note that an error appeared in the stiffness function in CR (b.) at steering ratio 1:12 at participant 14. That results in more steering wheel torque (RMS=2.824Nm) than the rest and is marked by the boxplot as an outlier. And is also noticeable in Steering wheel torque distribution (Appendix D - Vehicle).

Vehicle steering sensitivity

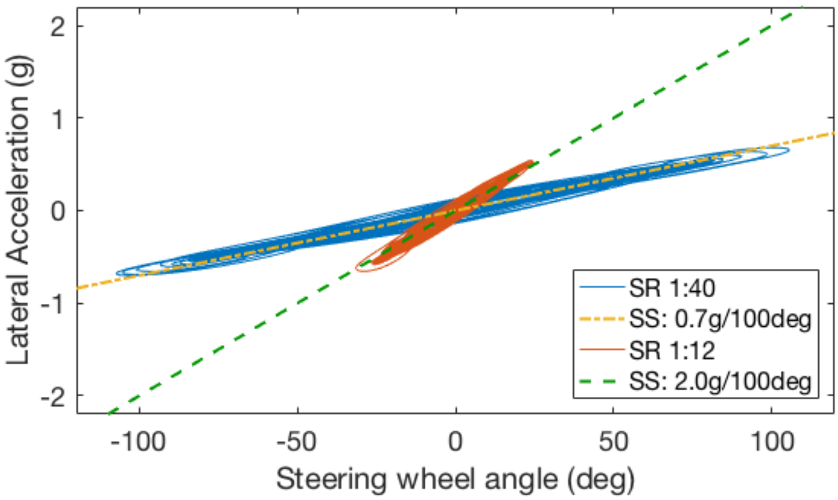


Figure D-3. Typical example (participant 18) for steering sensitivity on lateral acceleration (g) vs. steering wheel angle (deg) plots for steering ratio 1:40 (blue) and 1:12 (red) on country road (CR). Steering sensitivity lines for 0.7 and 2g/100deg seem to have approximately a similar slope as the simulator steering sensitivity. Lateral acceleration (m/s^2)/ gravitation (9.81 m/s^2) is Lateral acceleration (g).

Steering sensitivity is approximately 2g/100deg for the steering ratio 1:12 at 80km/h. Norman (1985) found a sports vehicle with steering sensitivity 1.97g/100deg (driving at 100kmh). For steering ratio 1:40 steering sensitivity is approximately 0.7g/100deg (CR) at 80km/h. That is within realistic limits (Salaani, Heydinger, & Grygier, 2004).

Vehicle characteristics

Table D-1. Vehicle dynamic parameters

Mass (kg)	1600	Width (m)	1.8
Yaw moment of inertia (kg m^2)	2000	Length (m)	4.0
		Wheel base length (m)	2.55

This study uses the same tire and vehicle dynamics model as was developed by R.M.A. Bekkers (2018)[1]. The tire characteristic parameters used for the Pacejka '94 tire model have been validated and tuned to differ front and rear tires slightly. The tire parameters used in this study are from the 'Passive configuration' tuning. The vehicle dynamic parameters were for mass 1856kg and velocity 100km/h, but for this study the parameters mass 1600kg and velocity 80 km/h are used.
Driving a curve with a radius of 60metres at 1600kg and velocity 80 km/h have similar lateral accelerations (approximately 8.3m/s^2, with lateral acceleration is velocity squared divided by curve radius[2]) as a curve negotiation of 93m radius at mass 1856kg and velocity 100km/h, like Bekkers' experiment (2018) near the Vehicle Handling Limit (VHL).

---

1 Bekkers, R.M.A. (2018) Driver behaviour near the vehicle handling limits in vehicles with an extended linear handling region, graduation report http://resolver.tudelft.nl/uuid:253c6741-2f97-4d4d-9c11-91fcbfeadf5b

2 https://en.m.wikipedia.org/wiki/Acceleration

The validated lateral tire force model with a vertical load of 4000N (about a quarter of the vehicle mass (Table D-1)) indicates that the non-linear region starts at a lateral force of 4000N (Bekkers, 2018). Therefore the tire-handling limit is not reached following the curved country road (CR) with a minimum curve radius of 100metres. The relation between lateral tire force and steering wheel angle in Figure D-2 is approximately linear.

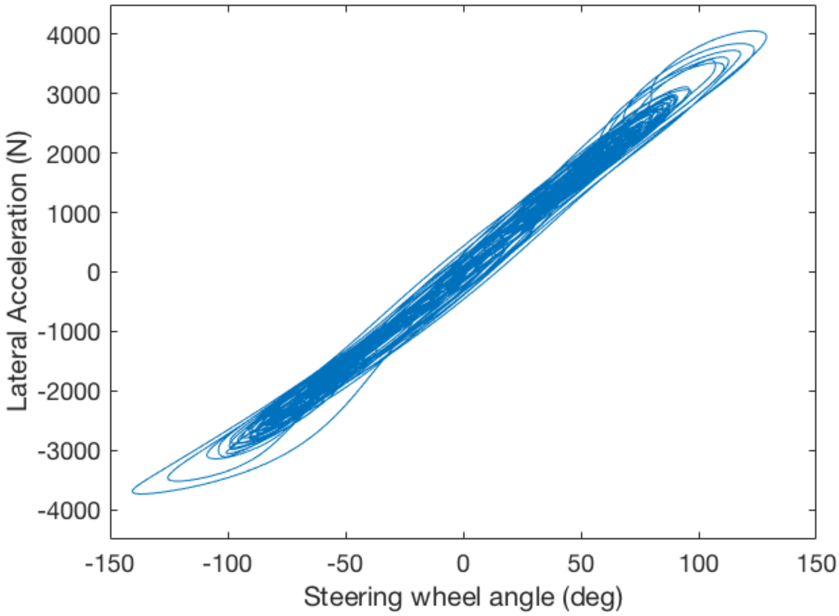


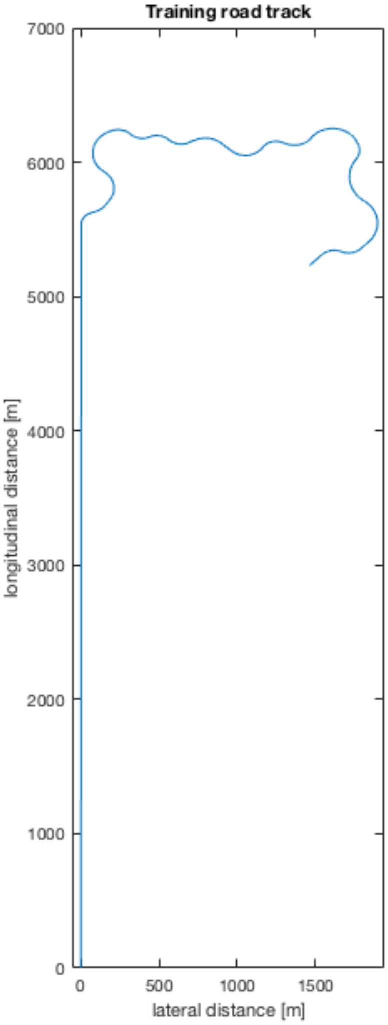
Figure. D-4 Typical example (participant 21, front left tire) for front lateral tire force of (N) vs. steering wheel angle (deg) plots for steering ratio 1:40 on country road (CR). Lateral tire force is approximately linear, although at the ends above 100 deg steering wheel angle is some hysteresis effect.

Appendix

E

Roads

Roads
Road lay-outs



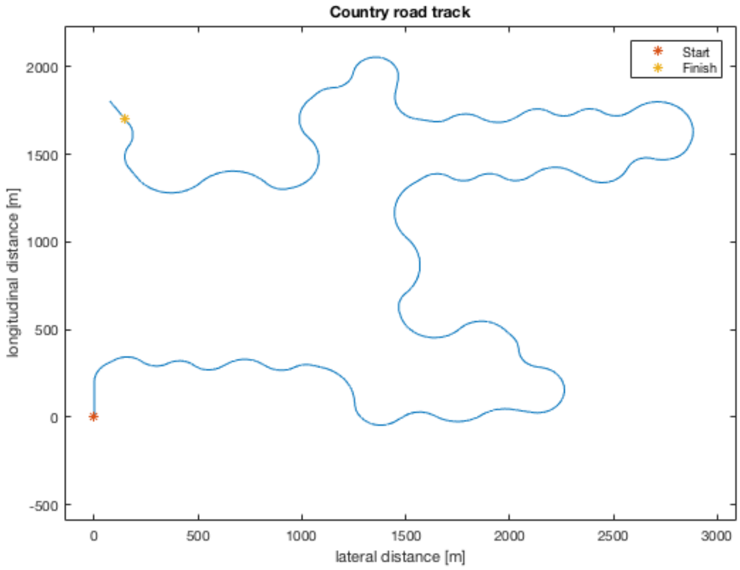


Figure E-2. Country road (CR) road lay-out in Longitudinal distance (m) and lateral distance (m) has a start at (0,0) (orange *) and a finish (yellow *)

Figure E-1. Training road lay-out in Longitudinal distance (m) and lateral distance (m) has the start at (0,0).

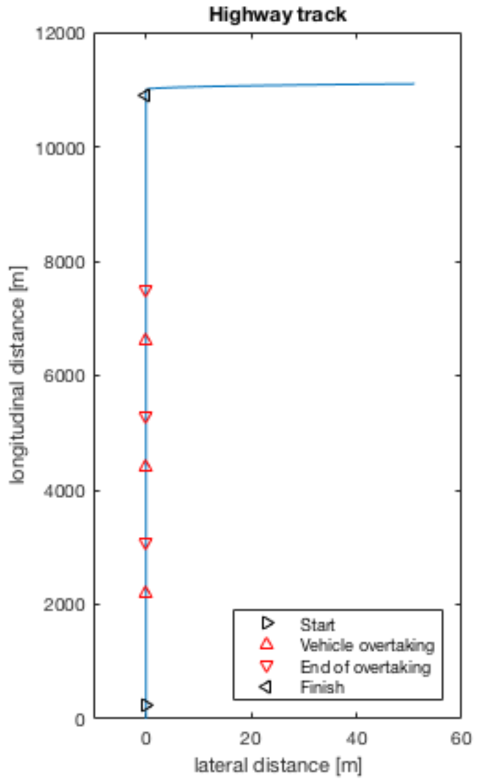


Figure E-3. Highway (HW) road lay-out in Longitudinal distance (m) and lateral distance (m) has a start at (black >) around (0,0) and a Finish (black <). Three overtaking manoeuvres start (red ^) with 'other vehicle in-sight' and end (red v) with being 'back at the right lane'.

		Tot. dist.(km)	Tot. time (s)	Analysed dist. (km)	Nr. Curves (L~R)
Training		9.582	431	-	8~10
	straight	5.532	248	-	none
	curvy	4.050	182	-	8~10
Country road		10.813	487	10.647	22~24
Highway		11.225	505	10.639 (w/o take-over 7.972)	none

Table E-1. Amount of distance, time and curves of the road profiles; Training with straight and curvy sections, Country road and highway. Total distance of track (km), total time (s) with velocity of 80km/h, distance (km) used for analysis from start to end (points) as indicated in the lay-outs (Fig. E-1,2,3) with additionally the distance without the three take-over sections (2.666 km) and number of left curves and right curves respectively.

Curve analysis

Curvatures of Training and CR

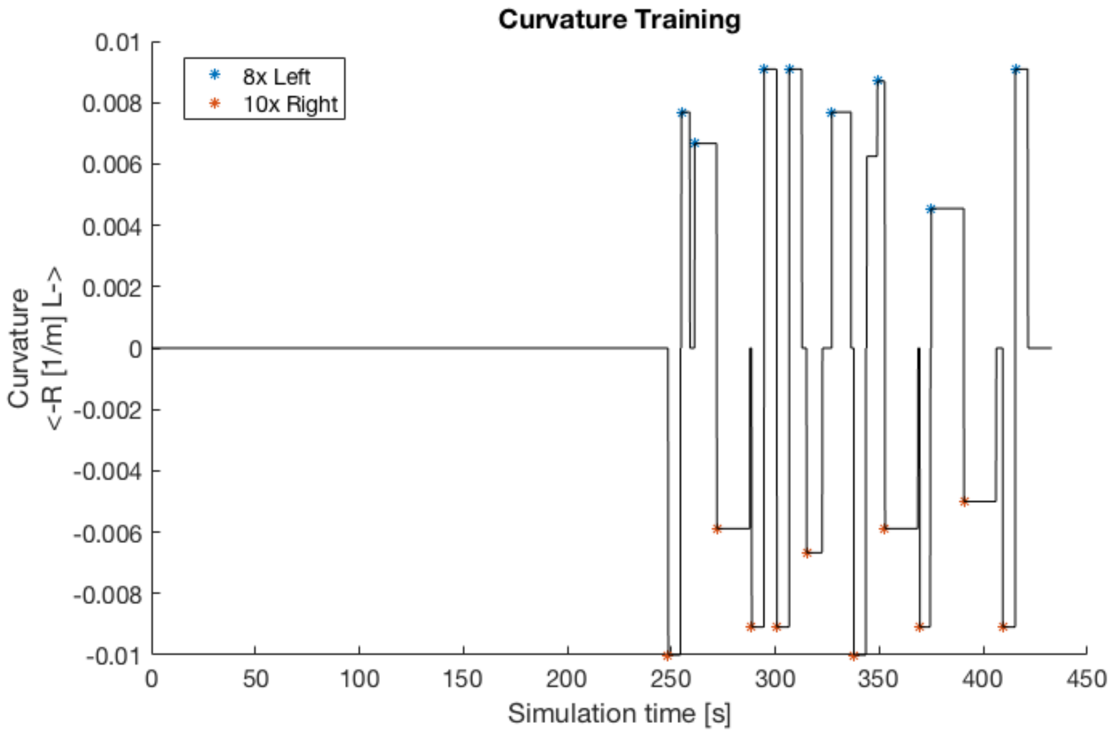


Figure E-4. Curvature of the Training road with curvature (1/m) and simulation time (s). Eight left curves (positive curvature) and ten right curves.

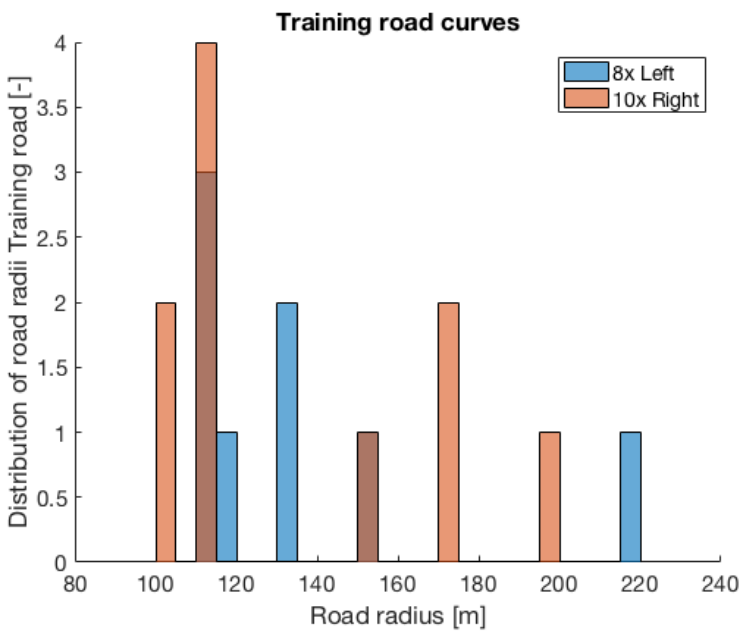


Figure E-5. Distribution of road radii (m) of the Training road; eight left curves (blue) and ten right curves (red).

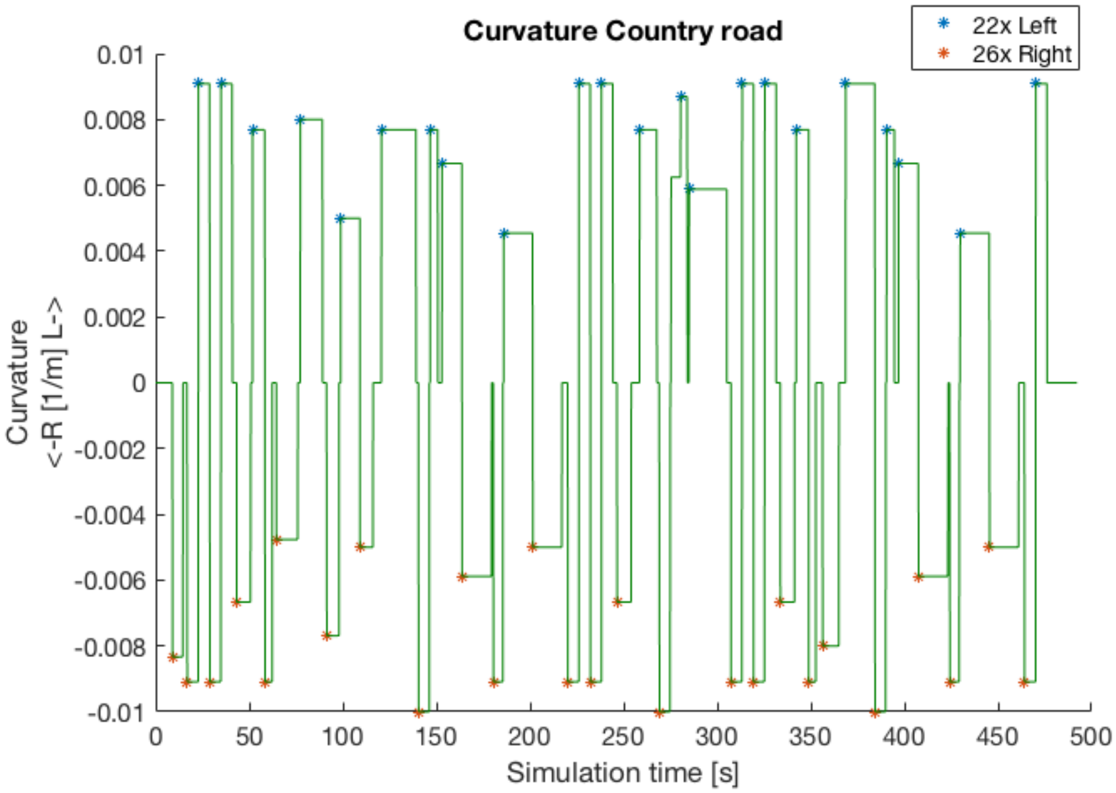


Figure E-6. Curvature of the Country road with curvature (1/m) and simulation time (s). 22 left curves (positive curvature) and 26 right curves.

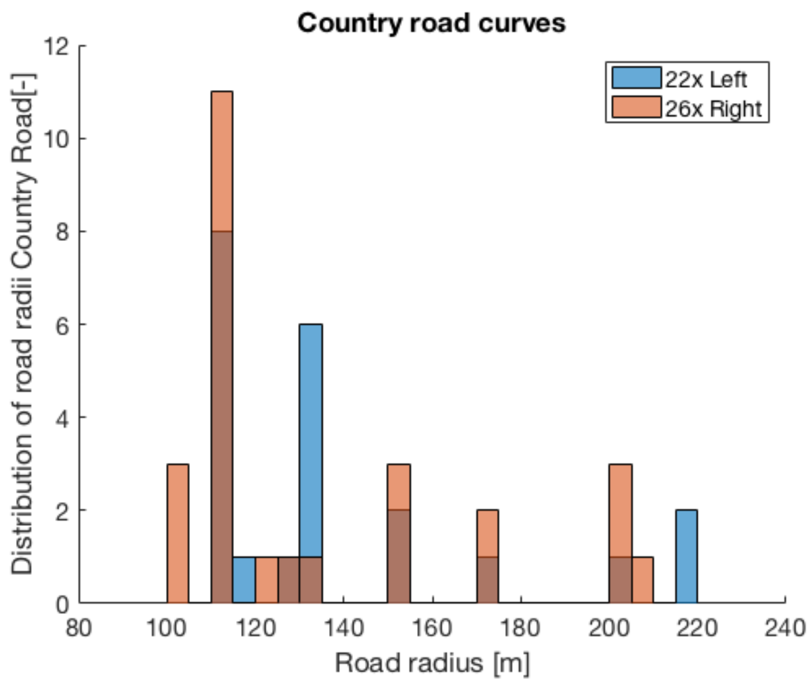


Figure E-7. Distribution of road radii (m) of the Country road; 22 left curves (blue) and 26 right curves (red).

Appendix

F

Instructions

Instructions

General instructions at the start

- Read and sign the 'Informed consent form'.
- Read the 'Steering feel questionnaire'.
- "Please, take place in the driving simulator seat and adjust the seat and backrest to reach comfortably to the steering wheel."
- Give the 'Briefing'
- Start the experiment condition (according to the sequence) with:
  "Are you ready? ok? 3…, 2…, 1…," [Start]
  … *[experiment running]*
  "Ok, that was it!" [Stop]
  "If you would not mind to step out and come over? I have a questionnaire here for you.".

Briefing

- You will drive at a constant speed of 80 km/h. So you do not have to use the pedals nor do any gear shifting, must only use the steering wheel.
- Keep your hands in the 10-to-2 position on the steering wheel.
  - Curve steering demands a steering wheel deviation of just over 90 degrees, so try also to keep the same grip there.
  - Straight driving has low steering wheel demand, but avoid leaning your hands/arms on your knees.
- On the straight section other traffic drives on the right lane. Please take over the vehicle on the left lane, no opposing traffic will occur. As soon as the vehicle is out sight on your right, you may assume it safe to return to the right lane, as rear/side mirrors are lacking. Unless taking over, keep to the right lane in both straight and curved road section.
- You are sitting on the driver seat on the left side of the vehicle and to your right is the passenger seat *(seat of the aviation simulator),* so to speak; same as standard European vehicles.
- Please indicate any signs of nausea/sickness if you experience any (especially before filling the 'nausea questionnaire').
- Right next to your knee is the emergency button, press it hard in case the steering wheel motor is malfunctioning.
- At the end of the track the asphalt stops and only grass is around, please notify me when you see that if not already stopped. I cannot see the road myself from the control room.

- This first run is a training round to make you familiar with the current steering wheel characteristics. This track consists of a straight section first followed by a curve section. Afterwards please come out of the simulator for a questionnaire.
- Thereafter two conditions both concluded with questionnaires follow.
- Then you are asked to do the training and the two conditions again with a different steering characteristics.
- Do you have any further questions? Please, let me know if you do.

Sequence of the experiment (according to the condition scheme)

- Training 1 (with steering ratio)
- 'Personal details questionnaire'
- Condition 1
- 'DSSQ, Steering feel, NASA-TLX and Nausea questionnaire'
  "Please cross or encircle the stripes of the NASA-TLX, not tick the boxes"
- Condition 2
- 'DSSQ, Steering feel, NASA-TLX and Nausea questionnaire'
  "You may compare to and/or edit the previous questionnaires"
- Training 2 (with other steering ratio)
- Condition 3
- 'DSSQ, Steering feel, NASA-TLX and Nausea questionnaire'
- Condition 4
- 'DSSQ, Steering feel, NASA-TLX and Nausea questionnaire'

Thank you very much for your participation!

Participants				**Conditions 1&2**			**Conditions 3&4**	
1	9	17	Training 1	IHW	ICR	Training 2	DHW	DCR
2	10	18		ICR	IHW		DHW	DCR
3	11	19		IHW	ICR		DCR	DHW
4	12	20		ICR	IHW		DCR	DHW
5	13	21		DHW	DCR		IHW	ICR
6	14	22		DHW	DCR		ICR	IHW
7	15	23		DCR	DHW		IHW	ICR
8	16	24		DCR	DHW		ICR	IHW

Steering ratio: D=Direct (1:12), I=Indirect (1:40),
Road type: HW=Highway, CR=Country road

Table F-1. Counterbalanced condition scheme

Appendix

G

Informed consent form

CONSENT FOR HUMAN PARTICIPANT RESEARCH

Shared calculation study

This is an invitation to participate in the research of master student R. Kroes. It is a study into the *effect of adjustments of the steering wheel characteristics on the driving experience in the vehicle*, where we want to investigate the benefits of *the implementation of such an active component in new vehicles*. You are invited to participate in this research, because you have a driver's license.

Research goals:
I try to find an answer to the following research question.
'What is the influence of adaptive/variable vehicle steering characteristics on driver experience and behaviour?'
The objective is to identify and gain knowledge about the relation of changes in vehicle dynamics and driving experience in the vehicle. Specifically, find the effect of adaptive 'steering wheel to vehicle wheel ratio'.

Description of the experiment:
In order to do that a human-in-the-loop experiment will be performed in the HMILab dueca simulator at the faculty of aerospace engineering of TU Delft. The participants will be asked to drive in the simulator at constant speed with two steering wheel configurations and two different roads: highway and country road. Before the participation they sign this form and fill in a form about their experience/skills in driving. After every condition the participants are asked to fill in two questionnaires: NASA-TLX and DSSQ. The collected subjective and objective data aims to quantify driving experience and driver behaviour accurately.

Procedure:

- Please drive the entire track as you normally would drive.
- If possible, drive on the right lane
- Keep both hands on the steering wheel, in a ten-to-two position

Confidentiality:
All data recorded in the experiment will be kept confidential and will only be used for research purposes. Data will be stored anonymously and will be made available only to persons conducting the study. Data will be achieved by the department Cognitive Robotics at 3mE TU Delft and erased according to their guidelines.

Risks and benefits:
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, you are advised to stop the experiment or rest for several minutes. As mentioned above, you can stop the experiment and withdraw at any time, without negative consequences. If you do not feel well, then please take sufficient rest before leaving the laboratory.

Participants rights: Participating in this experiment is entirely voluntary, you may discontinue participation at any time and refusal of participation will involve no penalty. You are requested to read and understand the information in this consent, prior to deciding whether or not to participate. You can ask questions about anything related to this experiment anytime.

Payment: Participating in this experiment will be entirely voluntary.

Contact details: For more information or concerns about this experiment please feel free to contact:
R. Kroes
r.m.m.kroes@student.tudelft.nl
Faculty of Mechanical Engineering - Delft University of Technology
Mekelweg 2 2628 CD Delft

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information above, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	□	□
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	□	□
Use of the information in the study		
I understand that information I provide will be used for a thesis report (published in the TU Delft repository) and possibly a publication.	□	□

Signature of participant ________________ Date ________________

Appendix

H

Questionnaires

i. Personal driving experience
ii. Results Personal driving experience
iii. DSSQ
iv. Acceptance questionnaire
v. NASA-TLX & Nausea

Simulator Study Personal details

Please make sure you fill out the questionaire before the driving experiment

* Required

1. **Participant number** *

2. **Gender**
   Mark only one oval.
   - Male
   - Female
   - Prefer not to say

3. **Age**

4. **How many years are you licensed to drive?**

5. **On average, how often did you drive a car in the last 12 months?**
   Mark only one oval.
   - Daily
   - 4-6 times per week
   - 1-3 times per week
   - Between once a week and once a month
   - Less than once a month
   - Never
   - Prefer not to say

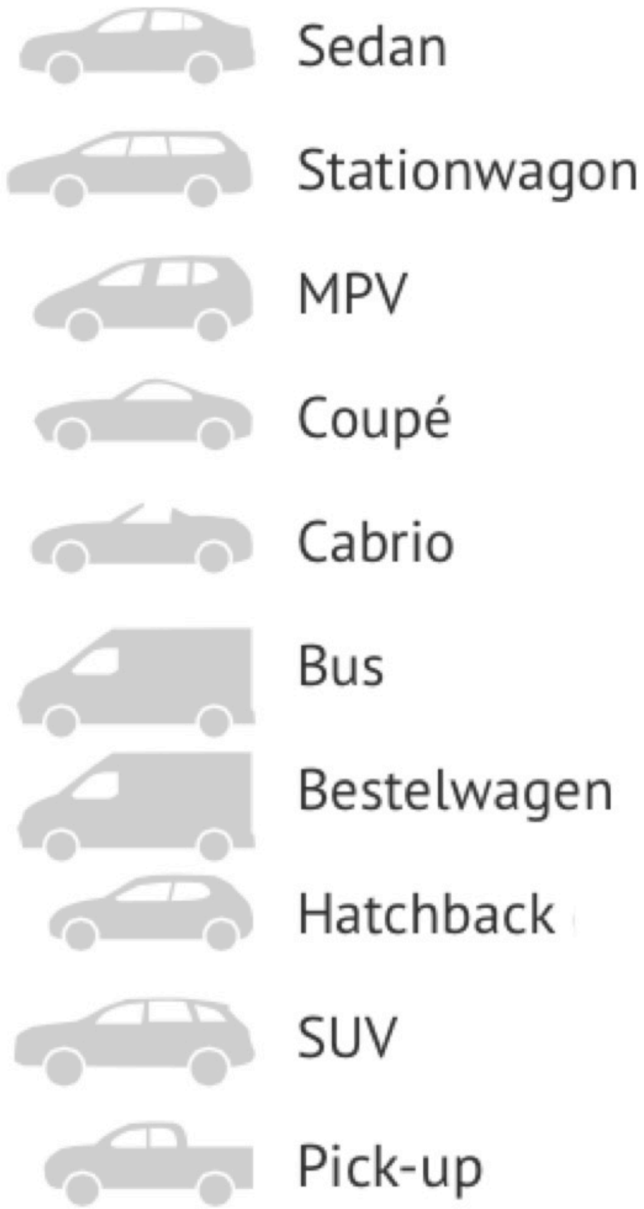
6. **How many kilometers did you drive in the last 12 months?**
Mark only one oval.

- 0
- 1-1.000
- 1.001-5.000
- 5.001-10.000
- 10.001-20.000
- 20.001-50.000
- 50.001-100.000
- over a 100.000
- Prefer not to say

7. **How many times do you play a (racing)game with real steering wheel?**
Mark only one oval.

- Daily
- 4-6 times per week
- 1-3 times per week
- Between once a week and once a month
- Less than once a month
- Never
- I don't know what Adaptive Cruise Control is
- Prefer not to say

8. **What type of car(s) did you drive?**



Check all that apply.

- [ ] Sedan / Stationwagon
- [ ] MPV
- [ ] Cabrio / Coupe
- [ ] Bus / Bestelbus
- [ ] Compact/Hatchback
- [ ] SUV

- [ ] Pick-up
- [ ] Other: ____________________

9. **How many accidents were you involved in when driving a car in the last three years?**
Mark only one oval.

   - ( ) 0
   - ( ) 1
   - ( ) 2
   - ( ) 3
   - ( ) 4
   - ( ) 5 or more
   - ( ) Prefer not to say

10. **How many times have you driven in a driving simulator?**
Mark only one oval.

   - ( ) 0
   - ( ) 1
   - ( ) 2
   - ( ) 3
   - ( ) 4
   - ( ) 5 or more

11. **How many times have you driven THIS driving simulator?**
Mark only one oval.

   - ( ) 0
   - ( ) 1
   - ( ) 2
   - ( ) 3
   - ( ) 4
   - ( ) 5 or more

Personal details driving experience
Simulator Study

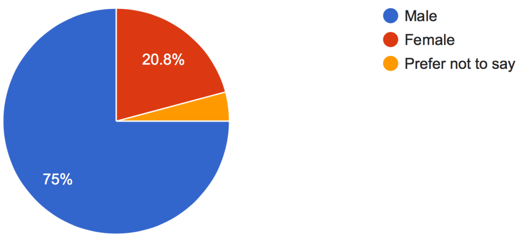
1. Participant number

   -

2.

Gender

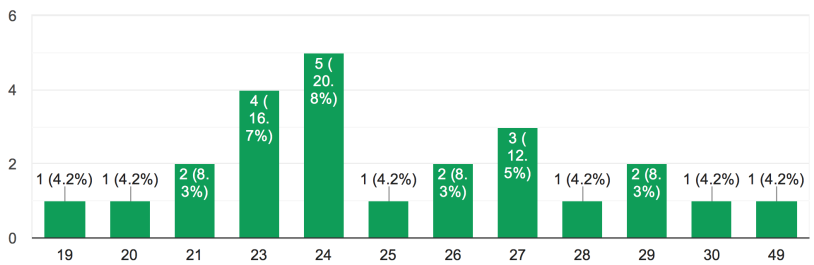
24 responses



3.

Age

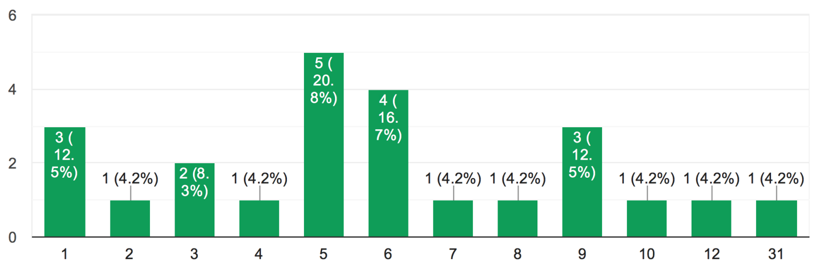
24 responses



4.

How many years are you licensed to drive?

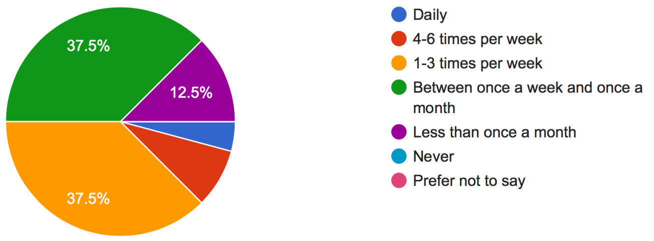
24 responses



5.

On average, how often did you drive a car in the last 12 months?

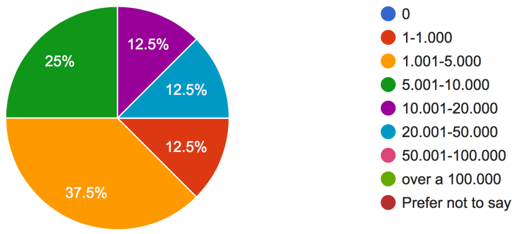
24 responses



6.

How many kilometers did you drive in the last 12 months?

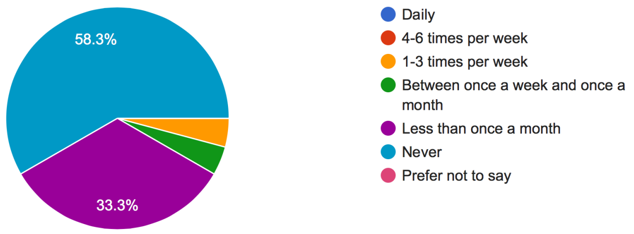
24 responses



7.

How many times do you play a (racing)game with real steering wheel?

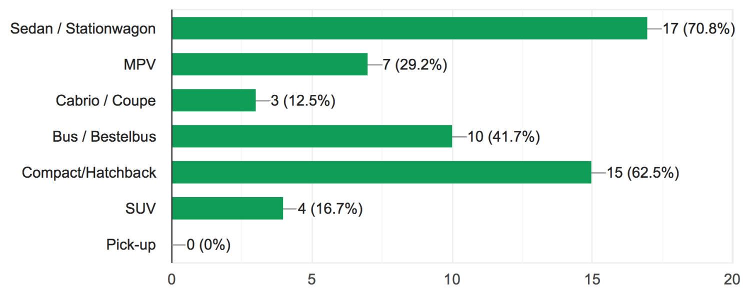
24 responses



8.

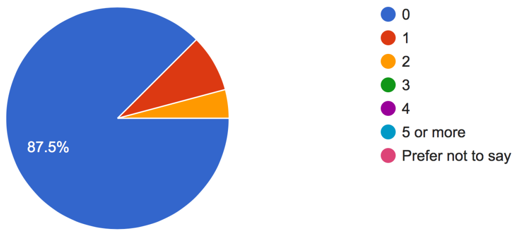
What type of car(s) did you drive?

24 responses



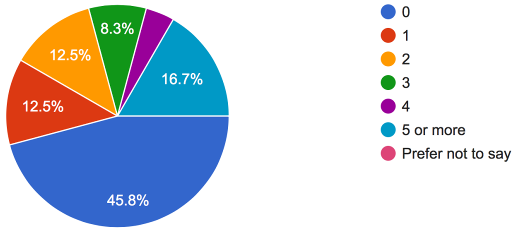
9.

How many accidents were you involved in when driving a car in the last three years?
24 responses



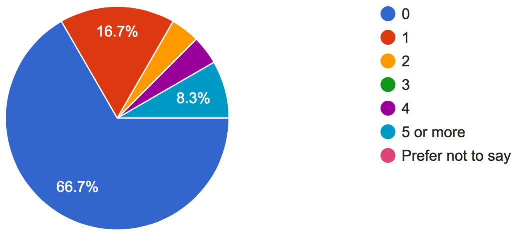
10.

How many times have you driven in a driving simulator?
24 responses



11.

How many times have you driven THIS driving simulator?
24 responses



DSSQ-3 STATE QUESTIONNAIRE (POST-TASK)

Instructions. This questionnaire is concerned with your feelings and thoughts while you were performing the task.
Please answer **every** question, even if you find it difficult. Answer, as honestly as you can, what is true of **you**. Please do not choose a reply just because it seems like the 'right thing to say'. Your answers will be kept entirely confidential. Also, be sure to answer according to how you felt **WHILE PERFORMING THE TASK**. Don't just put down how you usually feel.
You should try and work quite quickly: there is no need to think very hard about the answers. The first answer you think of is usually the best.

For each statement, **circle** an answer from 0 to 4, so as to indicate how accurately it describes your feelings **WHILE PERFORMING THE TASK**.

Definitely false = 0, Somewhat false = 1,
Neither true nor false = 2, Somewhat true = 3, Definitely true = 4

1.	I felt concerned about the impression I am making.	0	1	2	3	4
2.	I felt relaxed.	0	1	2	3	4
3.	The content of the task was dull.	0	1	2	3	4
4.	I thought about how other people might judge my performance	0	1	2	3	4
5.	I was determined to succeed on the task.	0	1	2	3	4
6.	I felt tense.	0	1	2	3	4
7.	I was worried about what other people think of me.	0	1	2	3	4
8.	Generally, I felt in control of things.	0	1	2	3	4
9.	My attention was directed towards the task.	0	1	2	3	4
10.	I felt energetic.	0	1	2	3	4
11.	I thought about how other people might perform on this task	0	1	2	3	4
12.	I thought about something that happened earlier today.	0	1	2	3	4
13.	I found the task was too difficult for me.	0	1	2	3	4
14.	I found it hard to keep my concentration on the task.	0	1	2	3	4
15.	I thought about personal concerns and interests.	0	1	2	3	4
16.	I felt confident about my performance.	0	1	2	3	4
17.	I examined my motives.	0	1	2	3	4
18.	I felt like I could handle any difficulties I encountered	0	1	2	3	4
19.	I was motivated to try hard at the task.	0	1	2	3	4
20.	I thought about things important to me.	0	1	2	3	4
21.	I felt uneasy.	0	1	2	3	4
22.	I felt tired.	0	1	2	3	4
23.	I felt that I could not deal with the situation effectively.	0	1	2	3	4
24.	I felt bored.	0	1	2	3	4

see the other side ---->

------**Steering Feel** ----

	← (-3) Totally disagree − disagree − somewhat disagree − neither agree nor disagree (0) − somewhat agree − agree − totally agree (3)→							
1.	I had the vehicle safely under control.	-3	-2	-1	0	1	2	3
2.	The control of the vehicle felt realistic.	-3	-2	-1	0	1	2	3
3.	I felt comfortable.	-3	-2	-1	0	1	2	3
4.	The vehicle responded realistically to steering movements.	-3	-2	-1	0	1	2	3
5.	I found the vehicle easy to control.	-3	-2	-1	0	1	2	3
6.	I found the vehicle course stable.	-3	-2	-1	0	1	2	3
7.	How soon does the vehicle react after you turn the steering wheel?	← delayed						quick →
		-3	-2	-1	0	1	2	3
		← poor						good →
8.	How do you like this configuration of the steering overall?	-3	-2	-1	0	1	2	3

Thank you.

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.

Participant no:	Controller	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

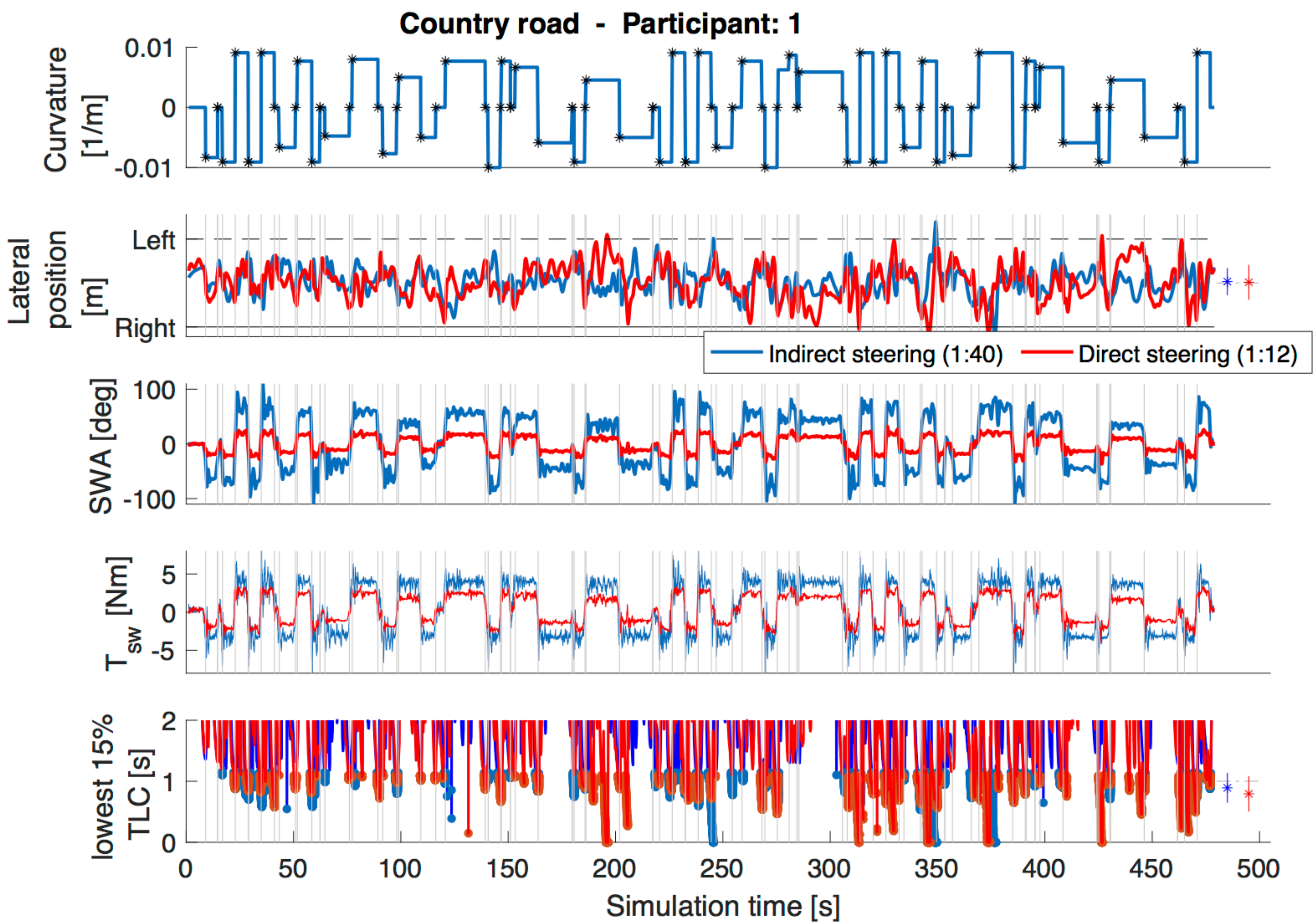
Nausea: To what extend do you experience nausea? Please circle the statement that is most fitting to your condition.

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

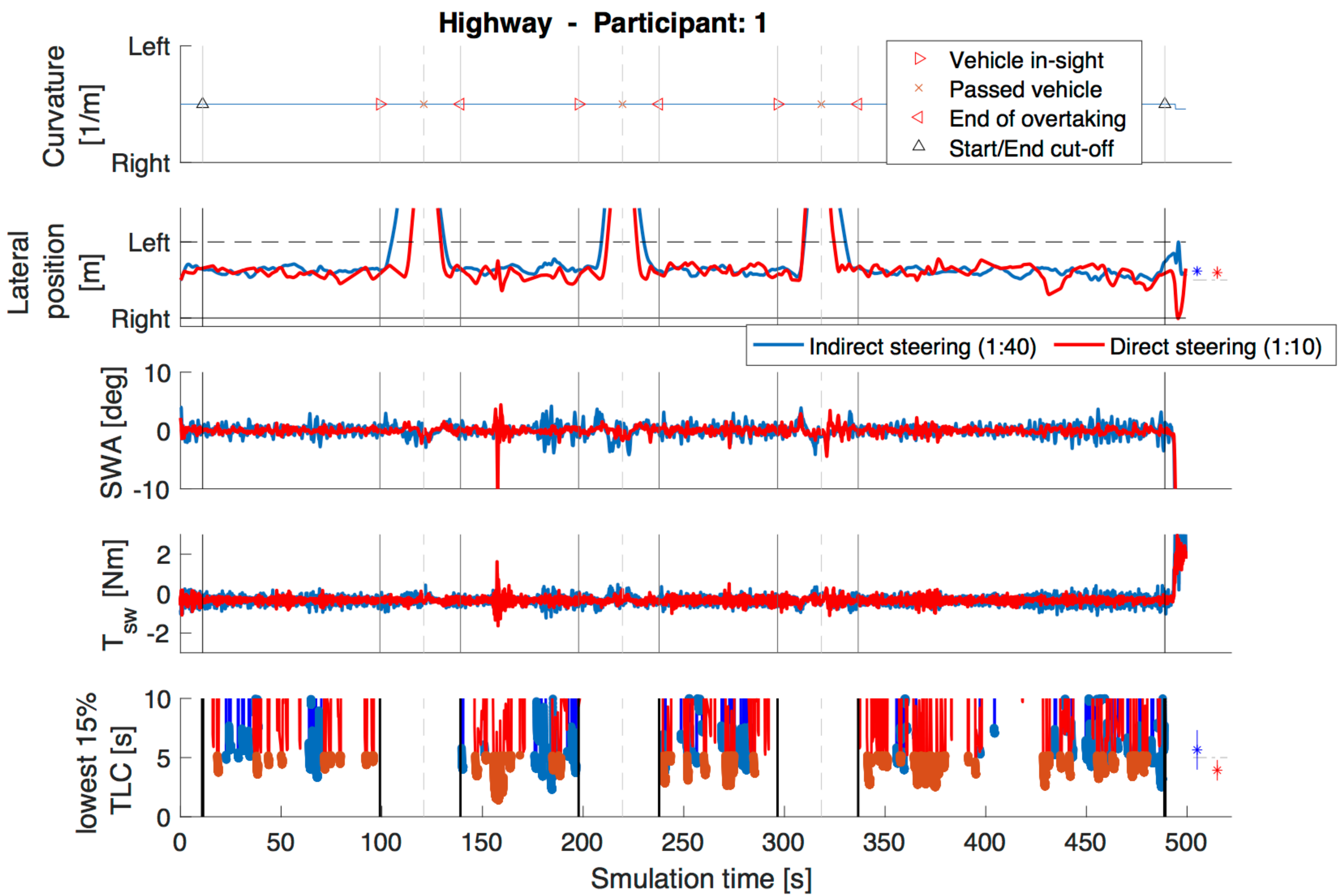
Appendix

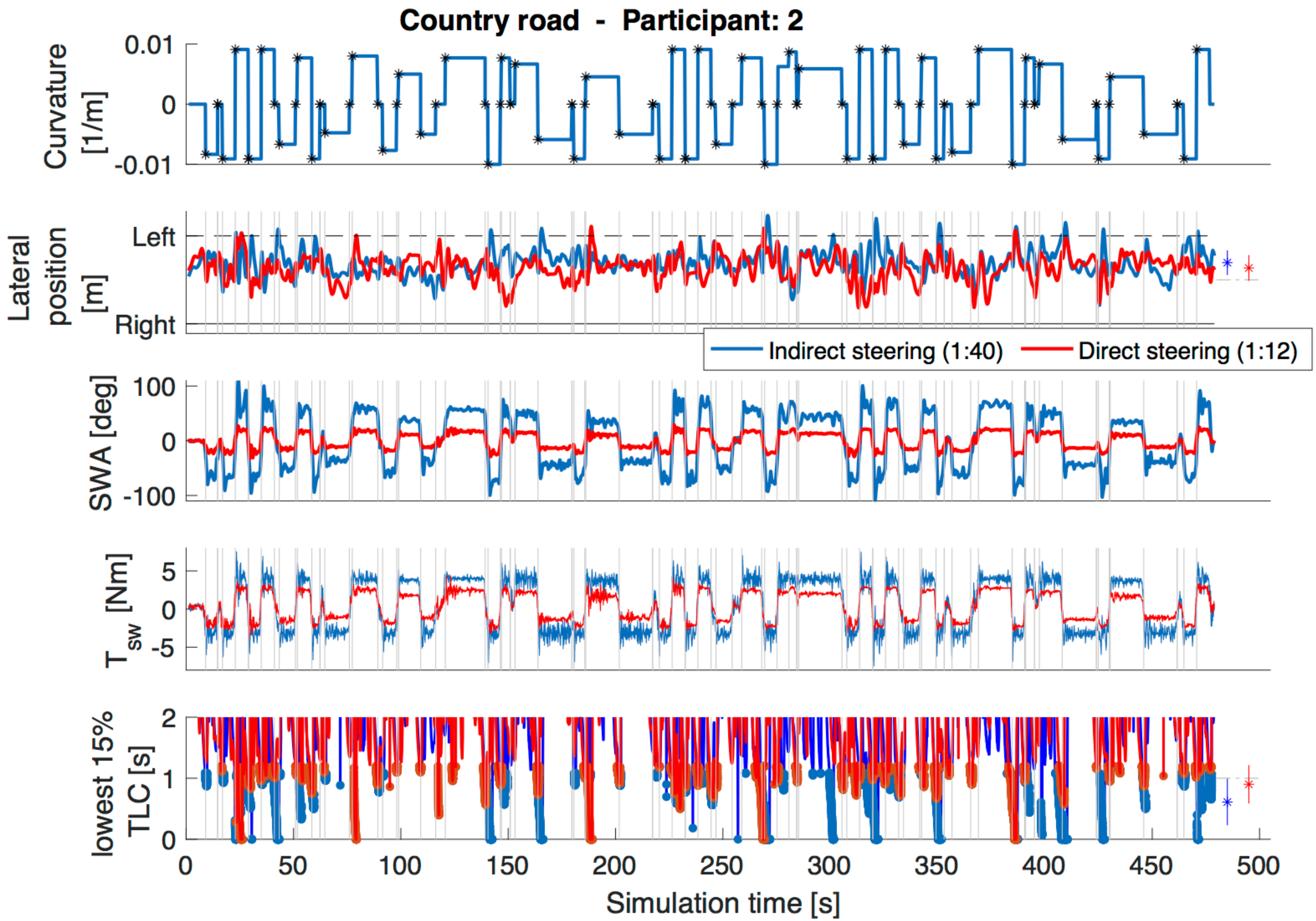
I

Individual results

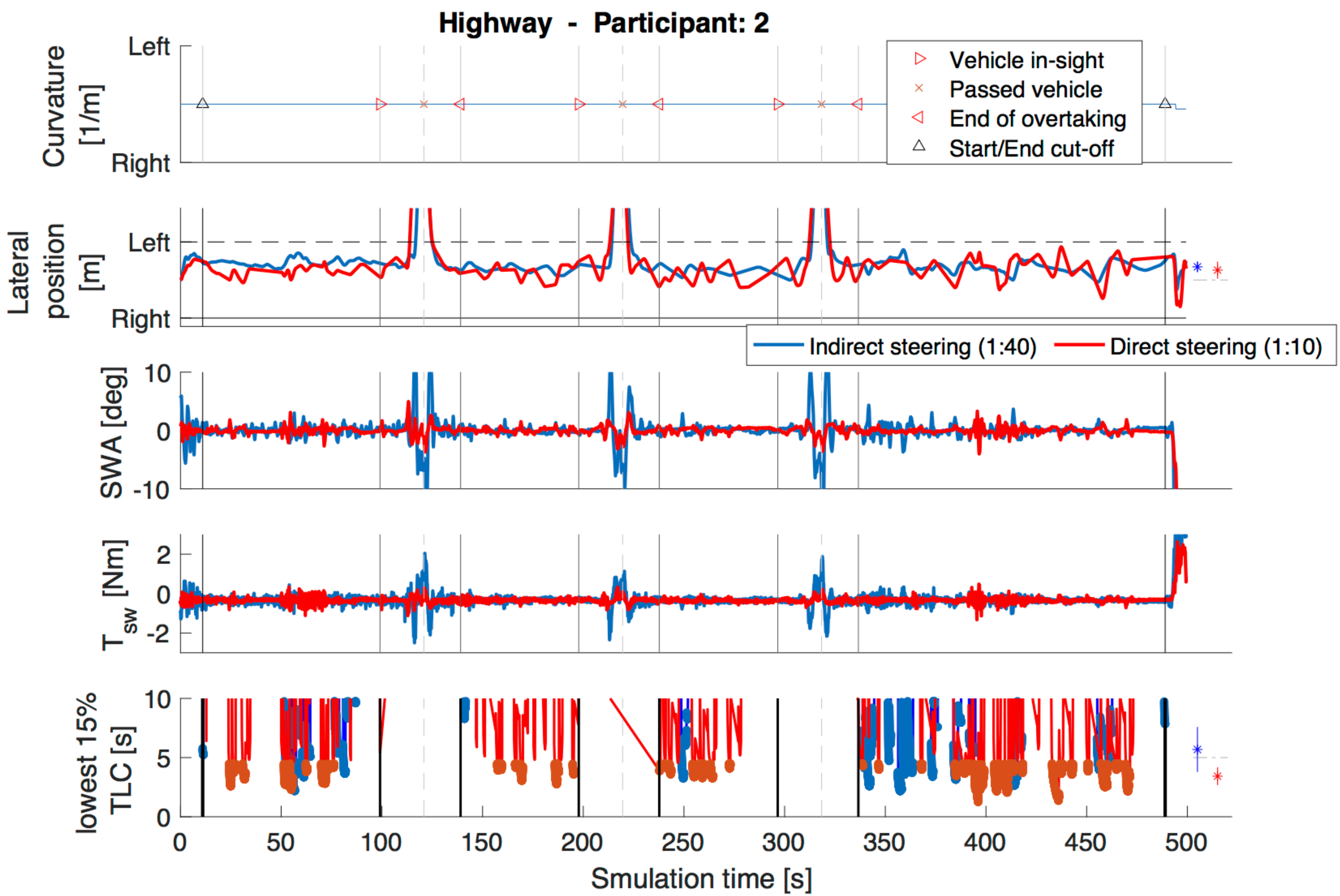


Country road - Participant: 1
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

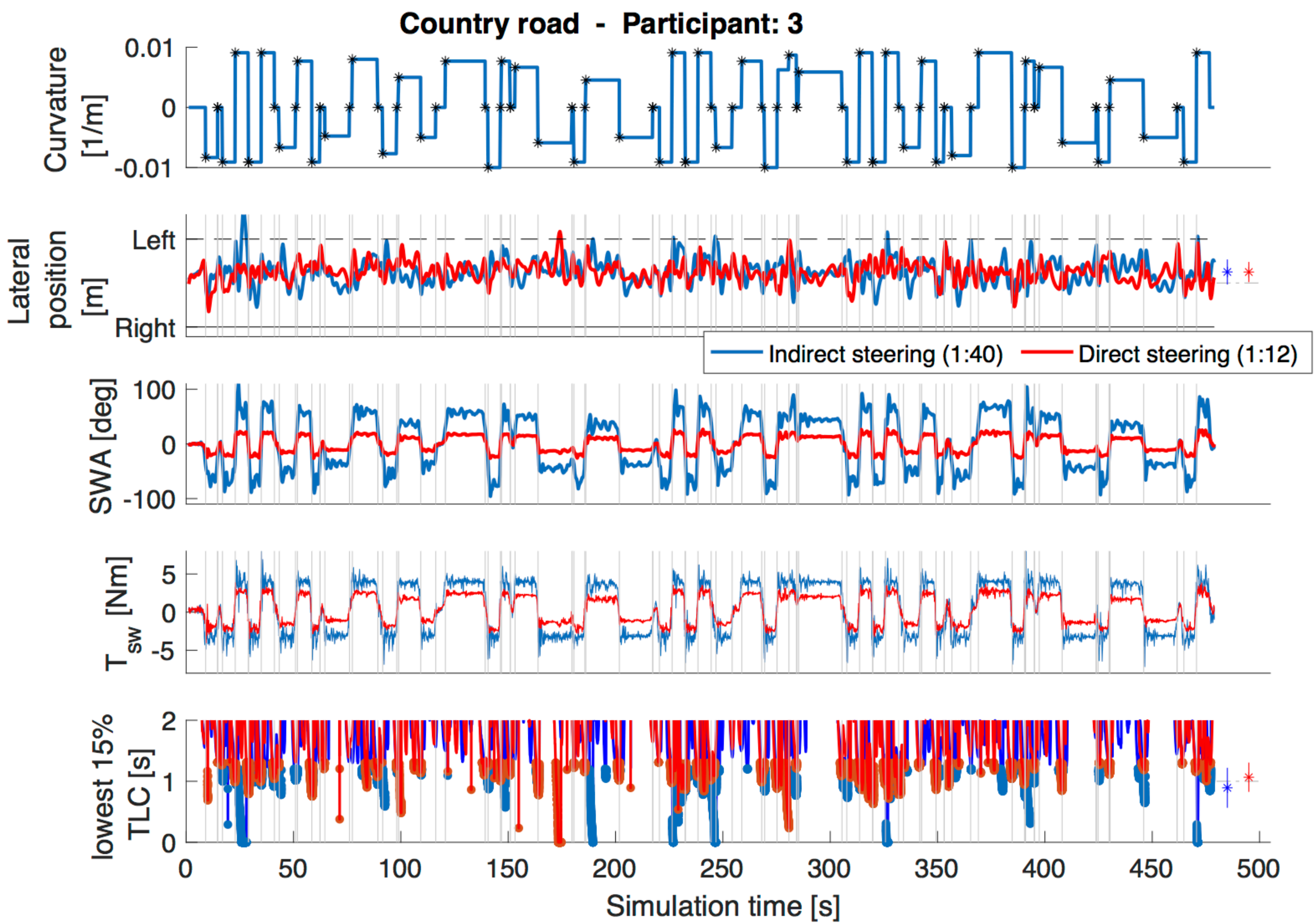

Highway - Participant: 1
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

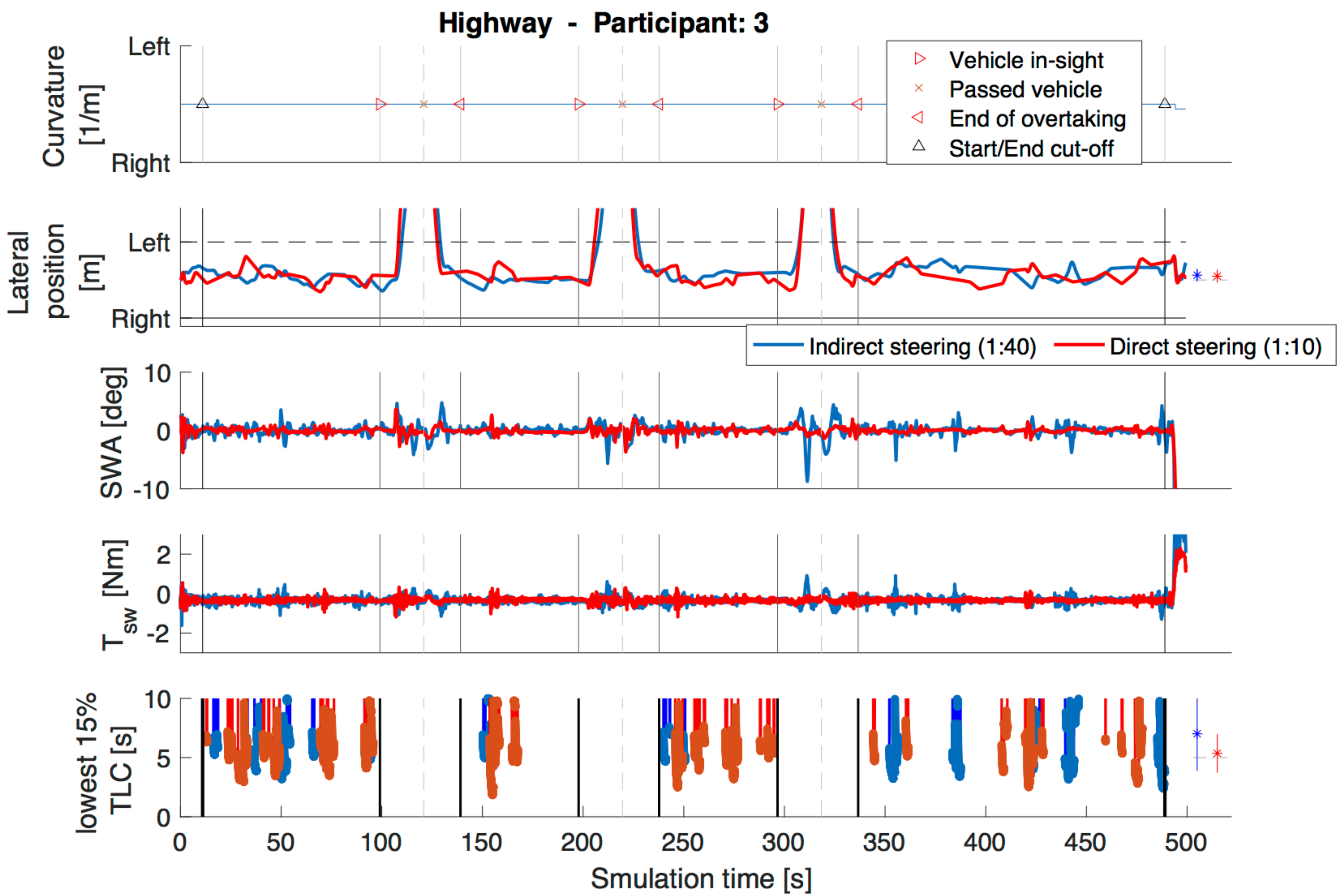


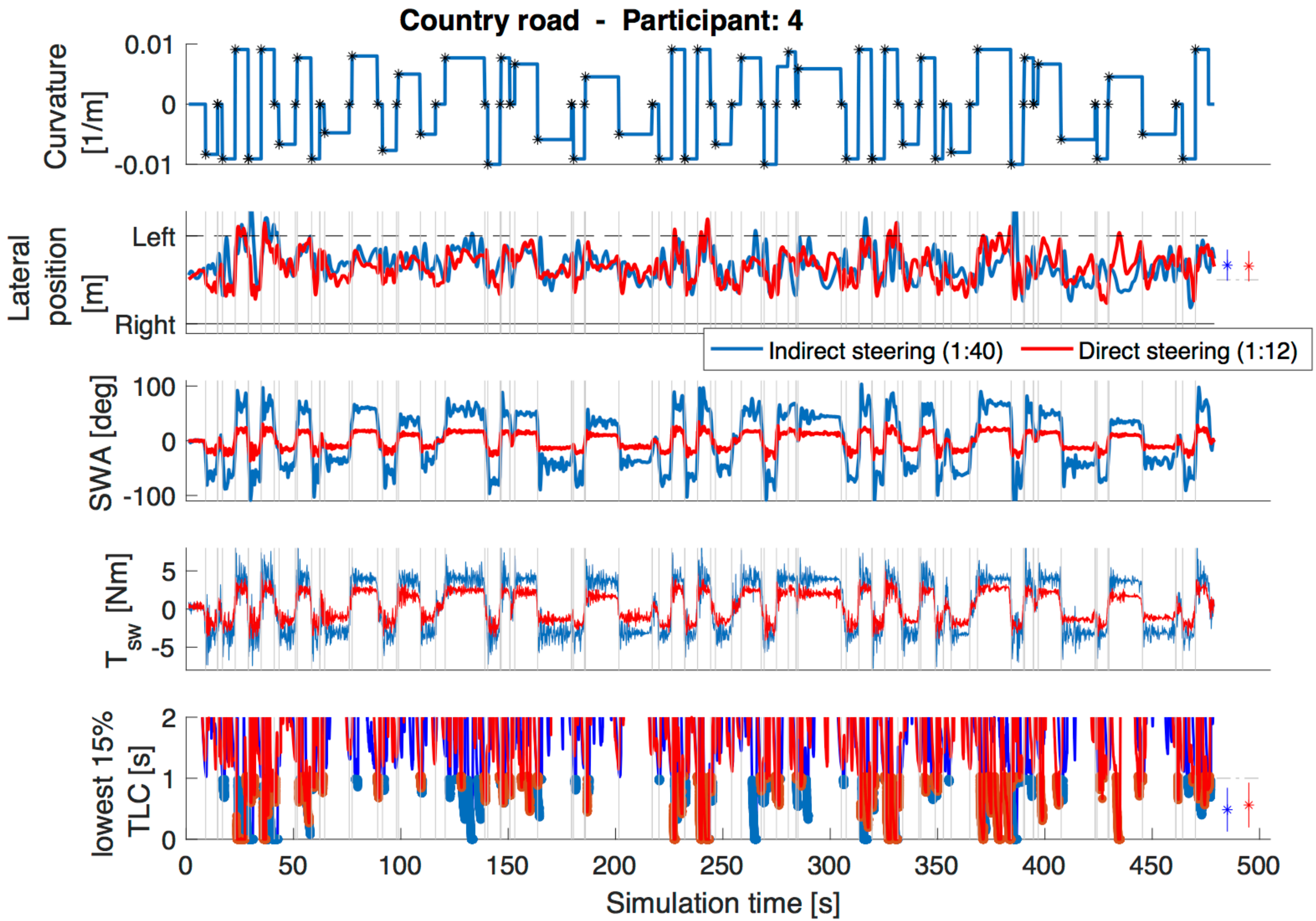
Country road - Participant: 2
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

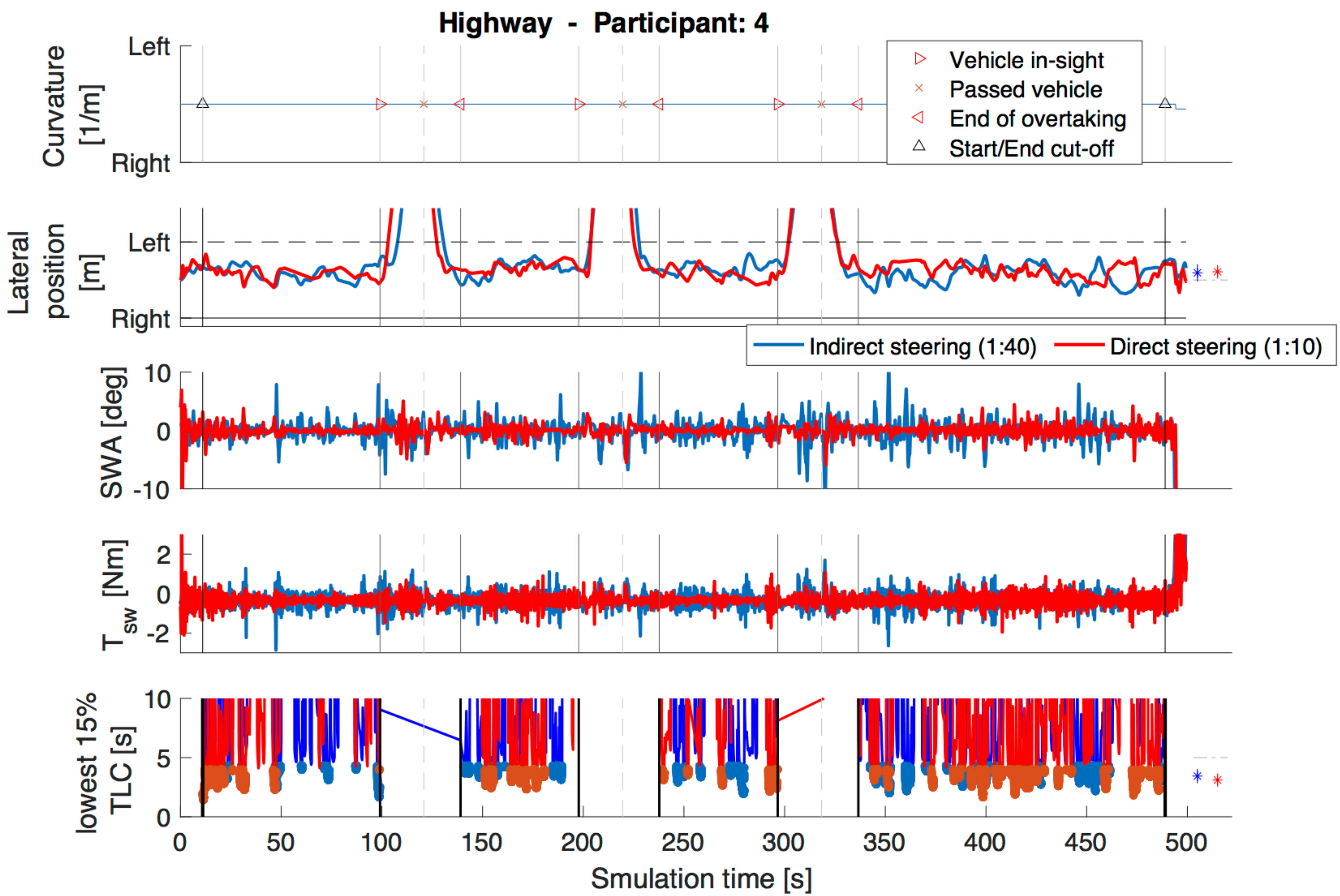


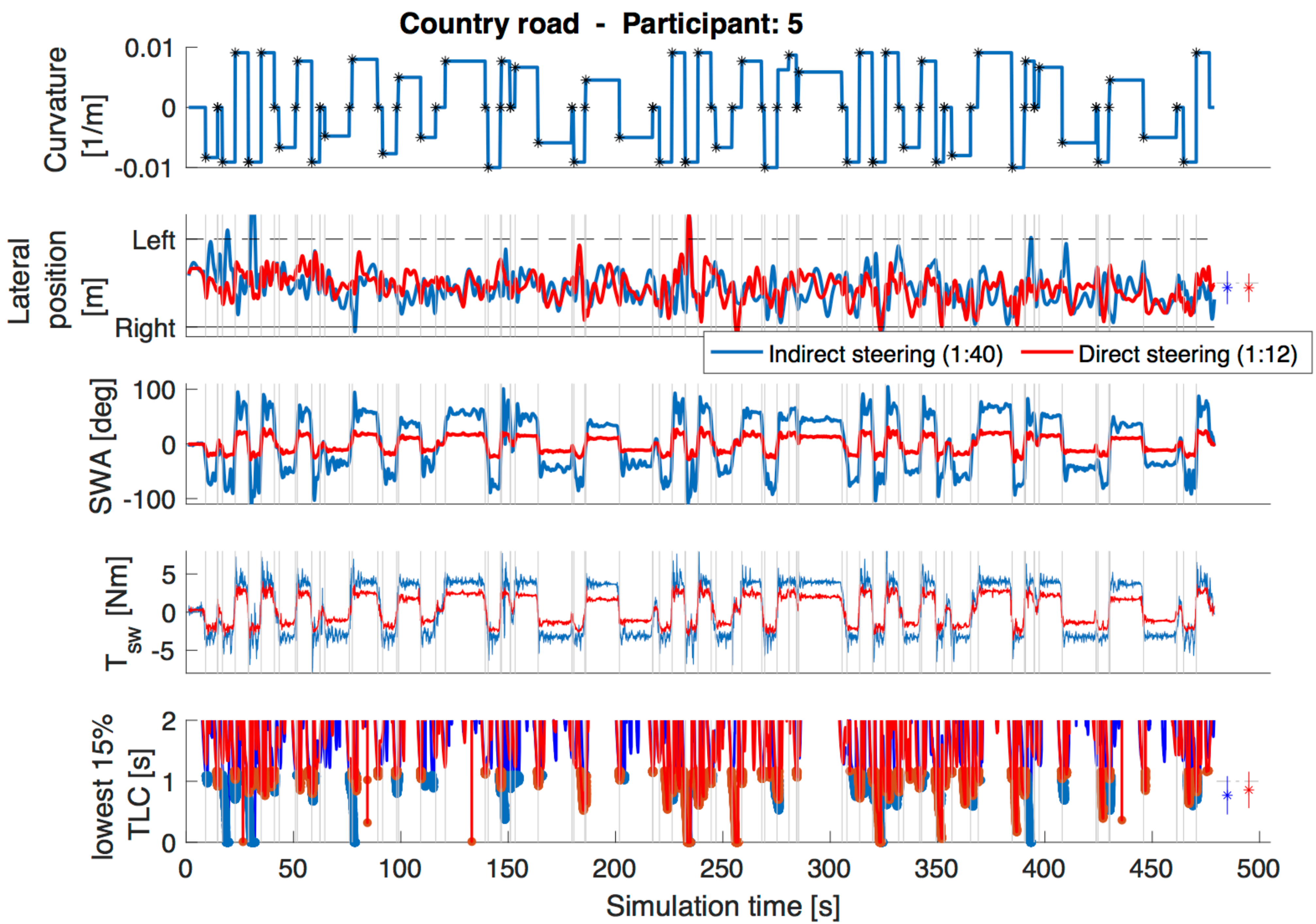
Highway - Participant: 2
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]


Country road - Participant: 3
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

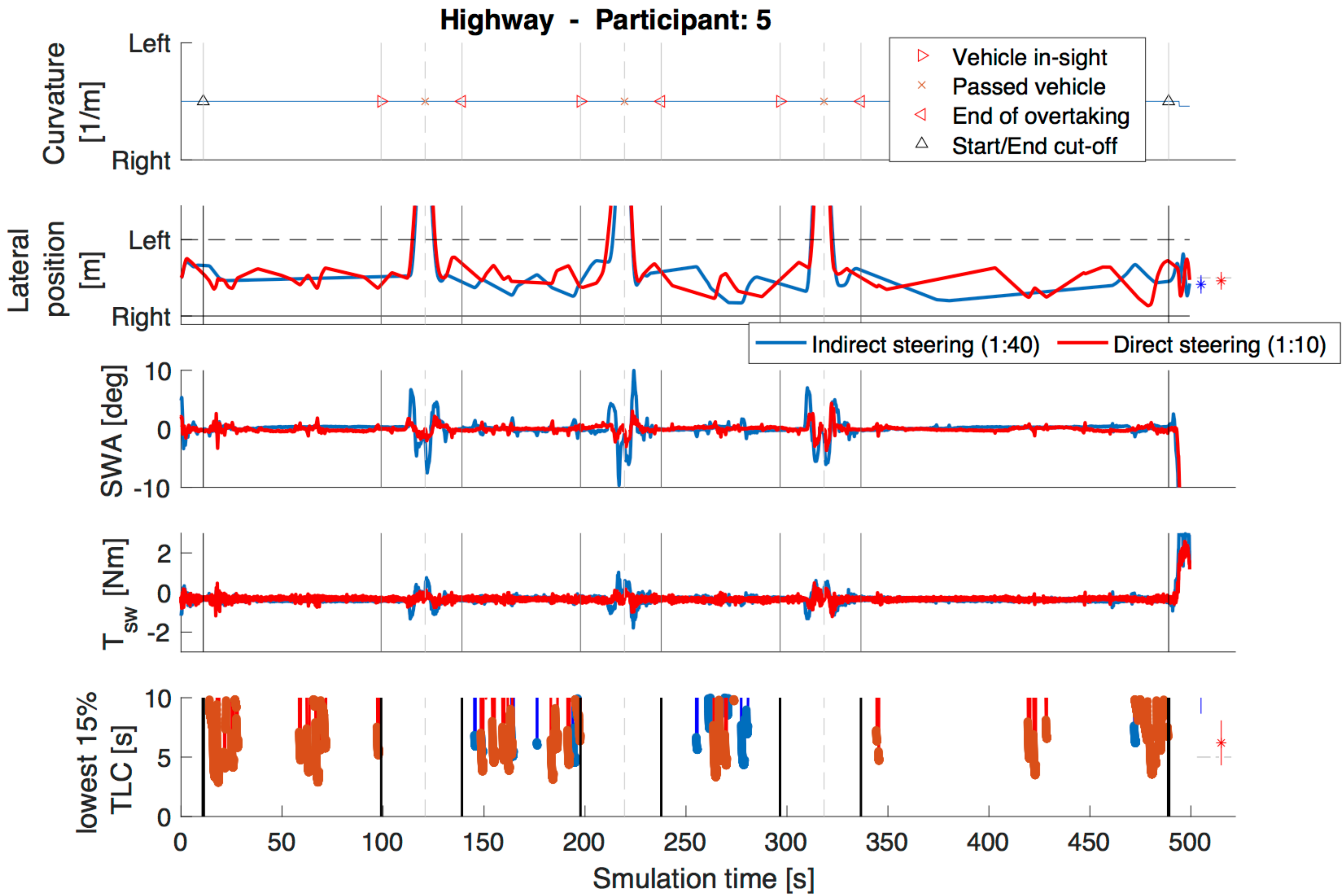

Highway - Participant: 3
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]


Country road - Participant: 4
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

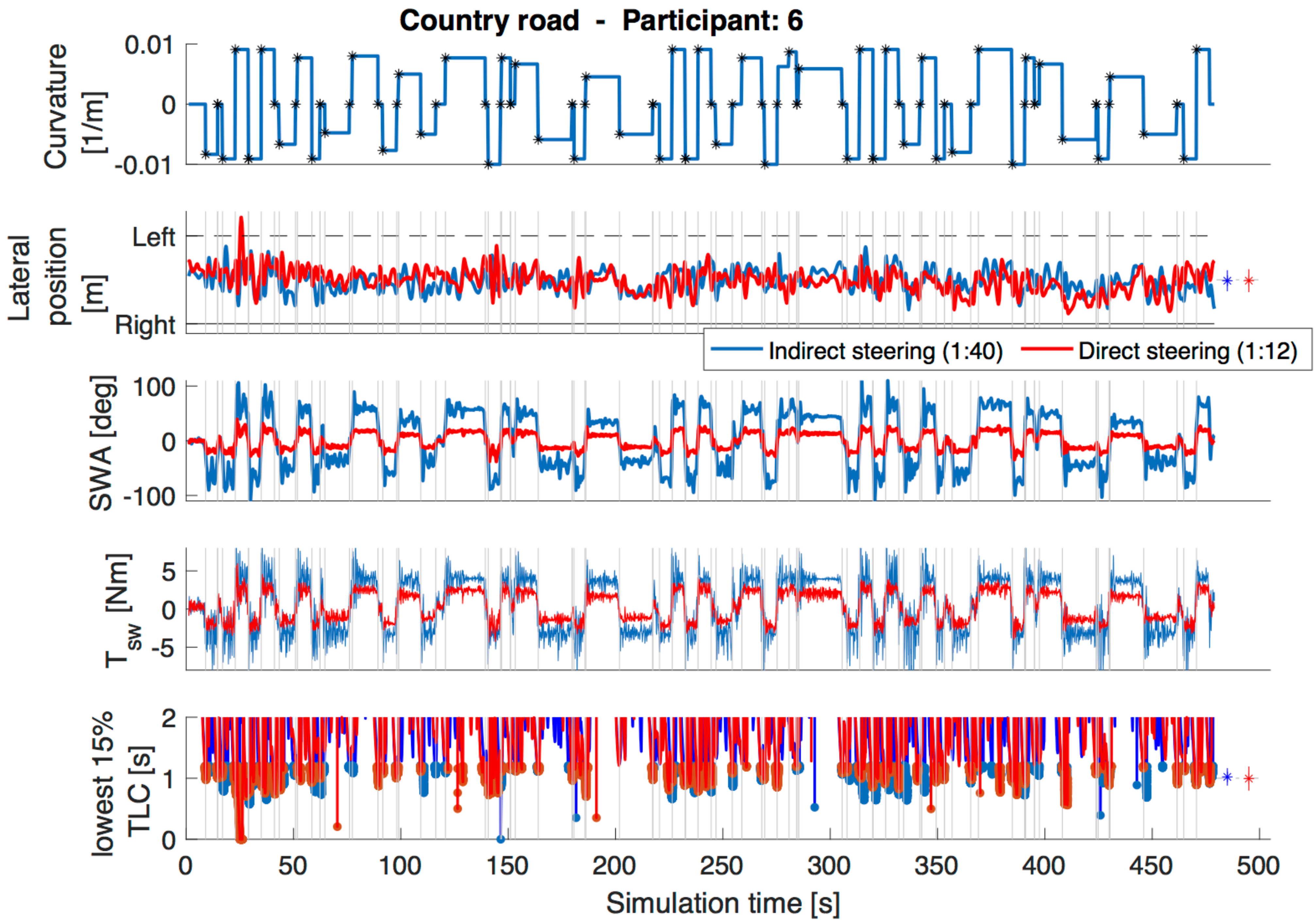

Highway - Participant: 4
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

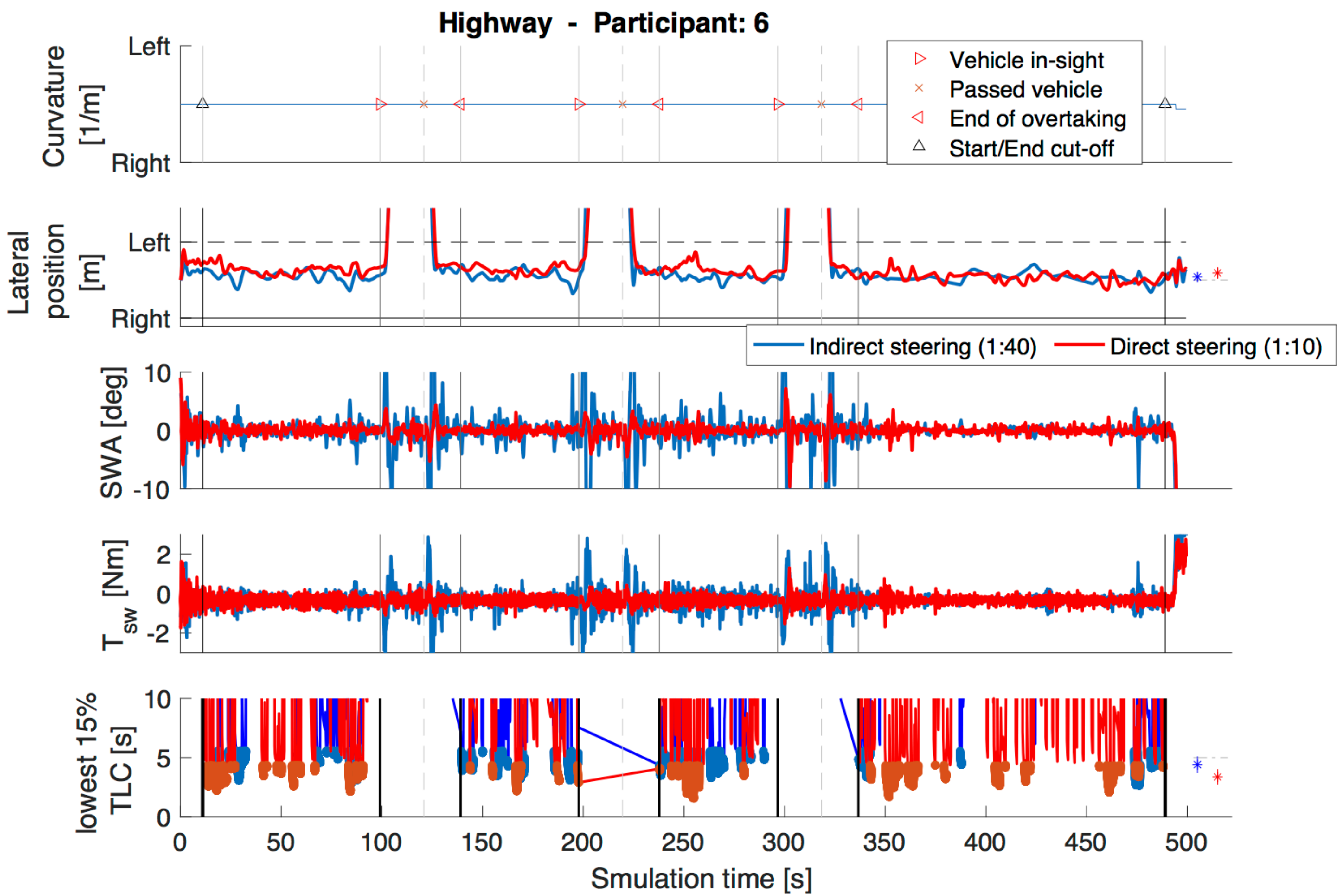


Country road - Participant: 5
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T sw [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

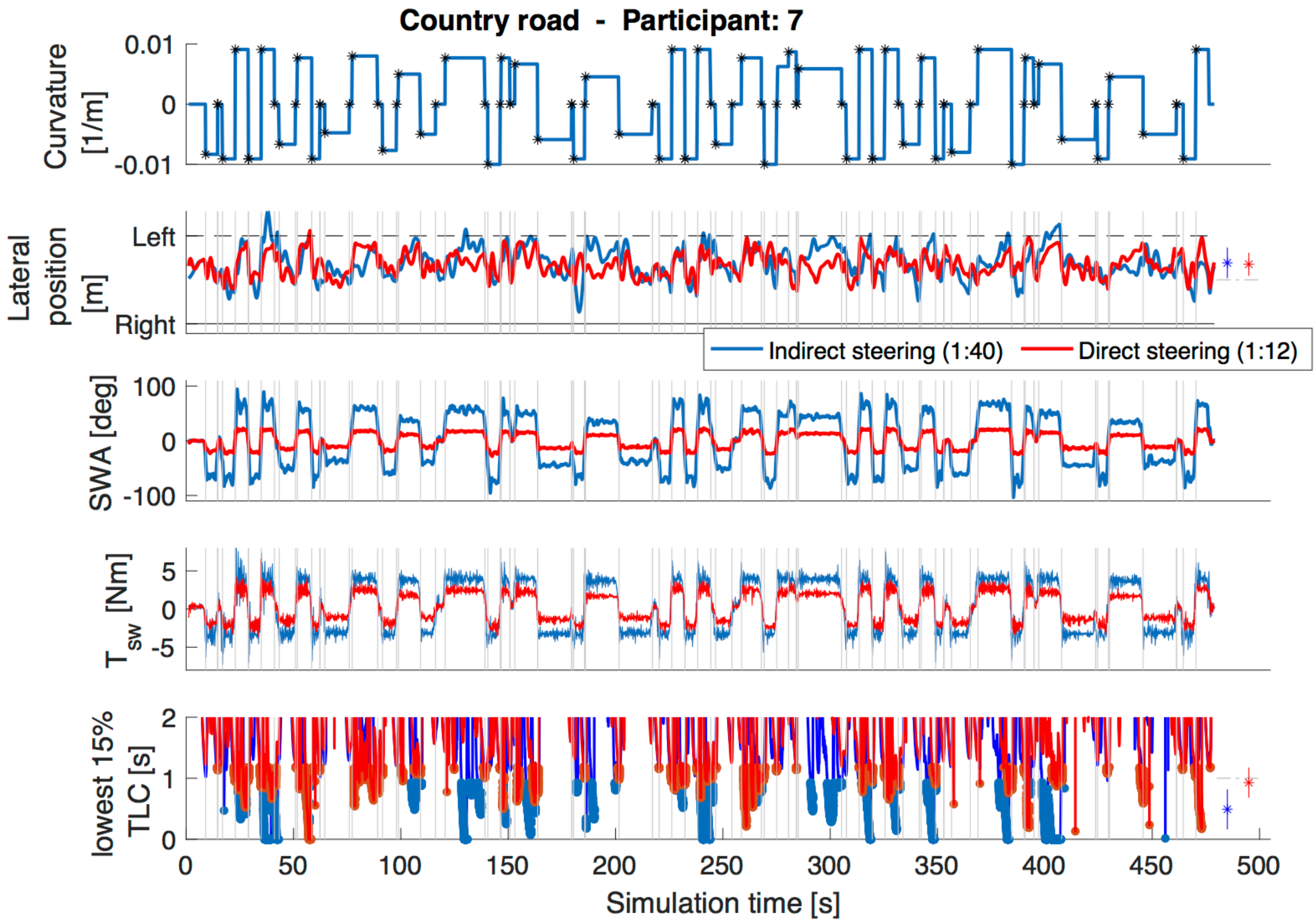


Highway - Participant: 5
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T sw [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

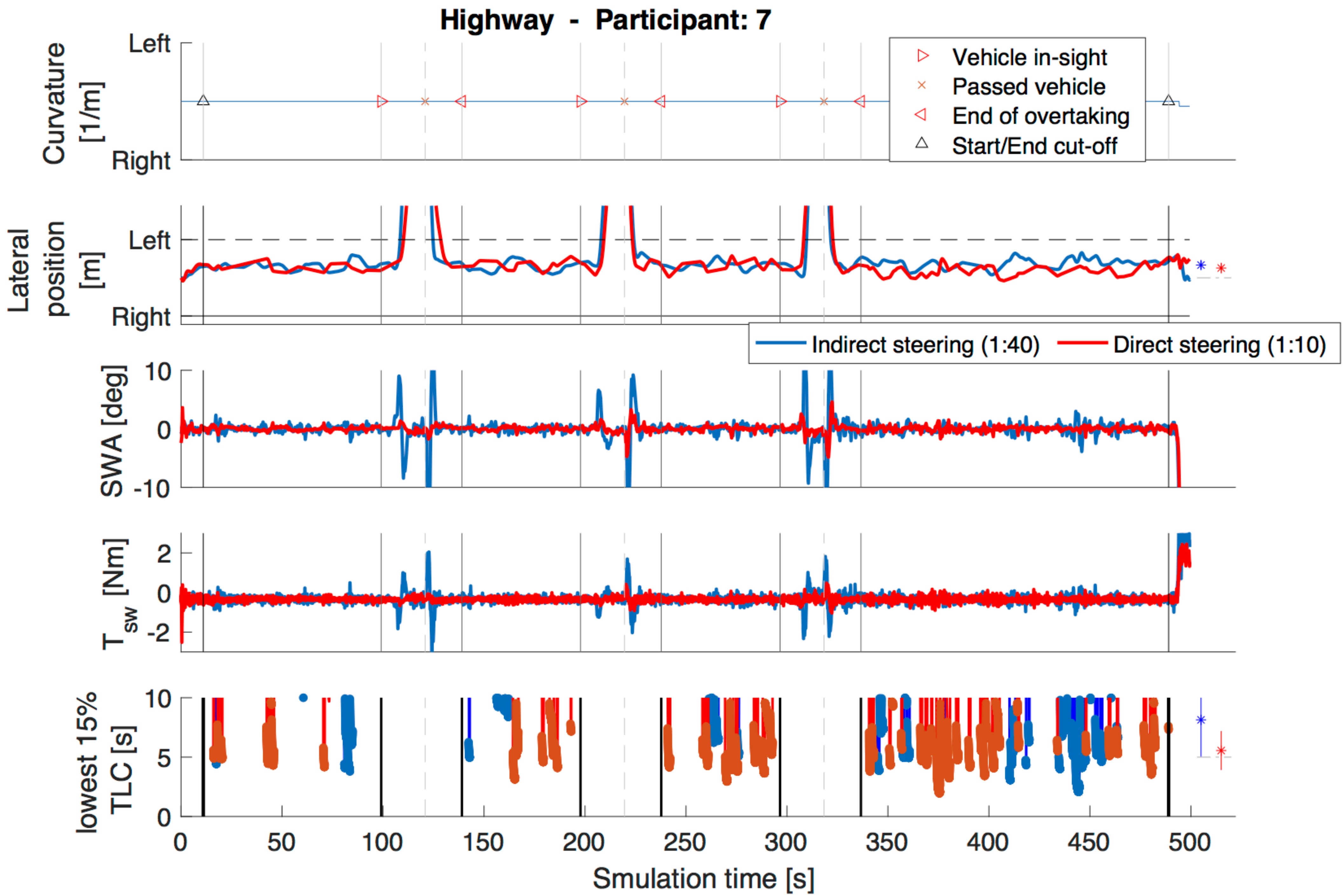

Country road - Participant: 6
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_sw [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



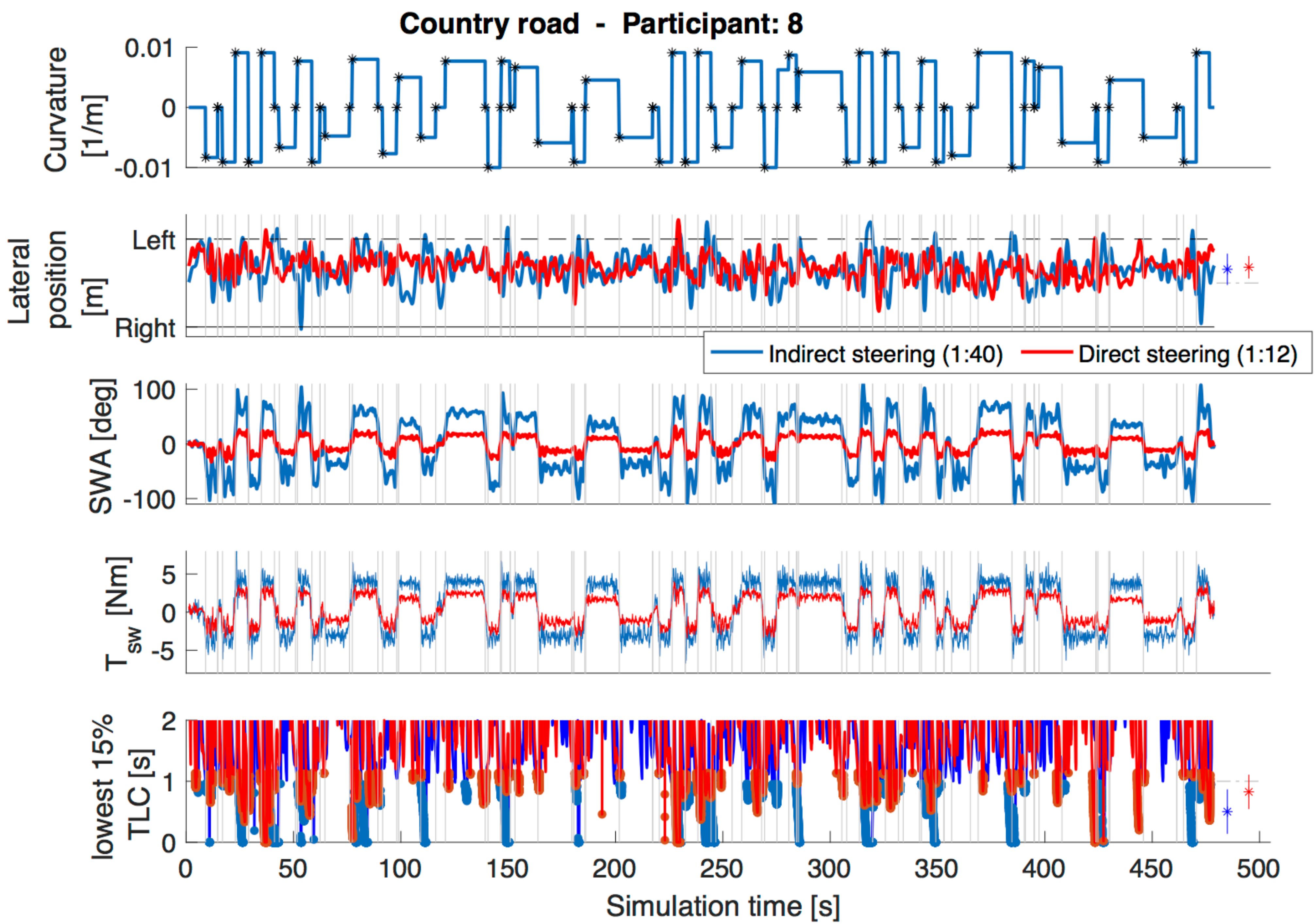
Highway - Participant: 6
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]



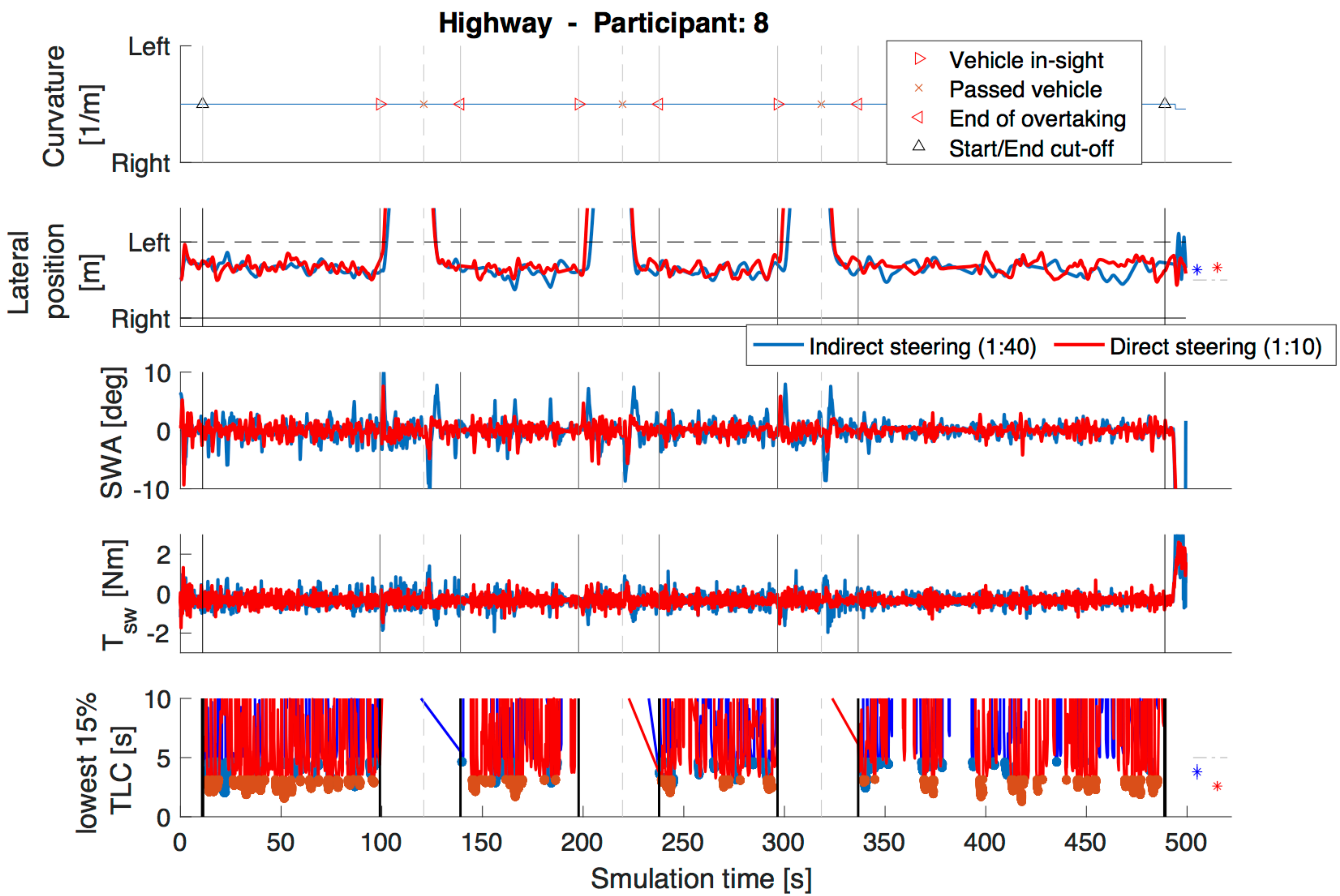
Country road - Participant: 7
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



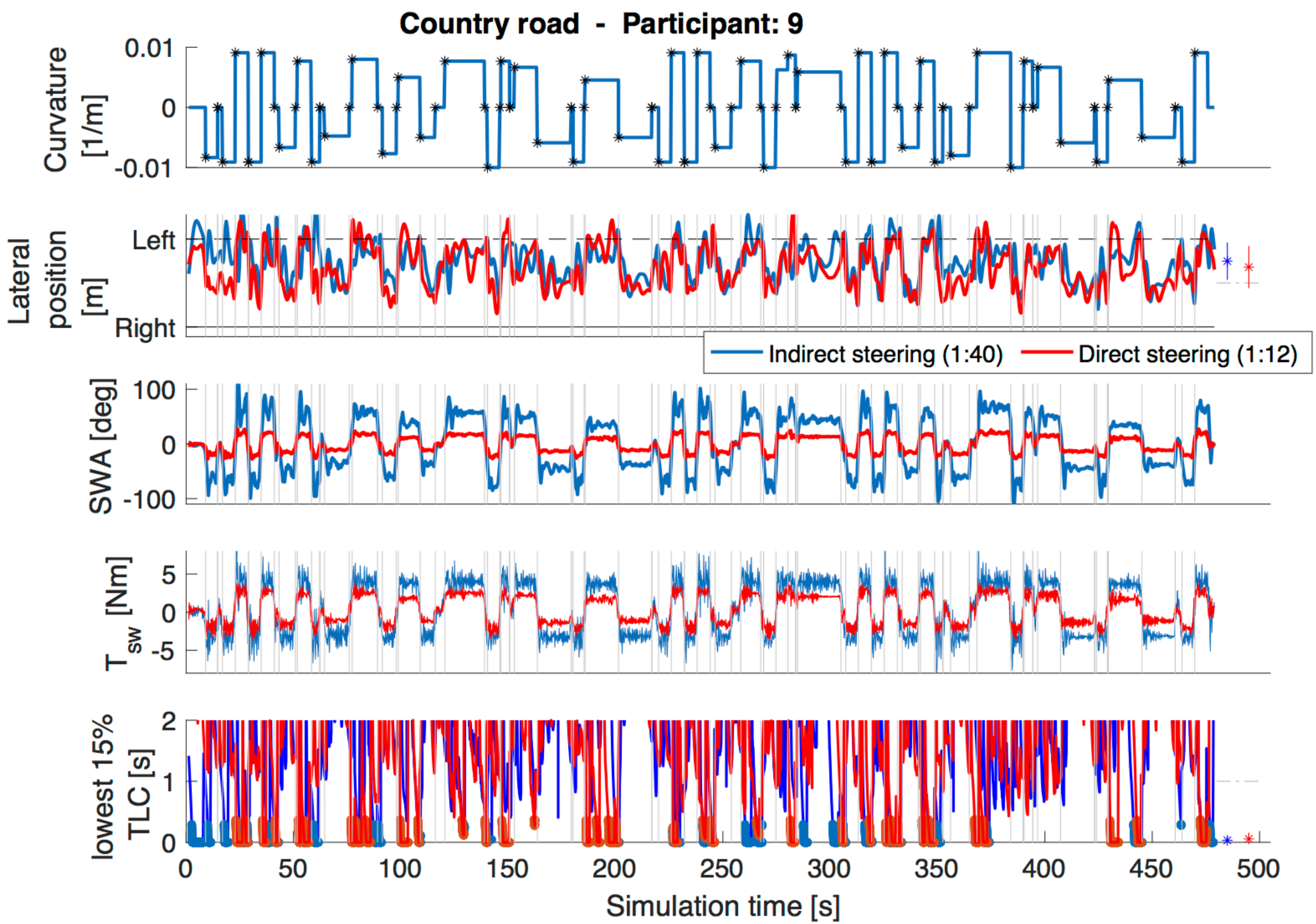
Highway - Participant: 7
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

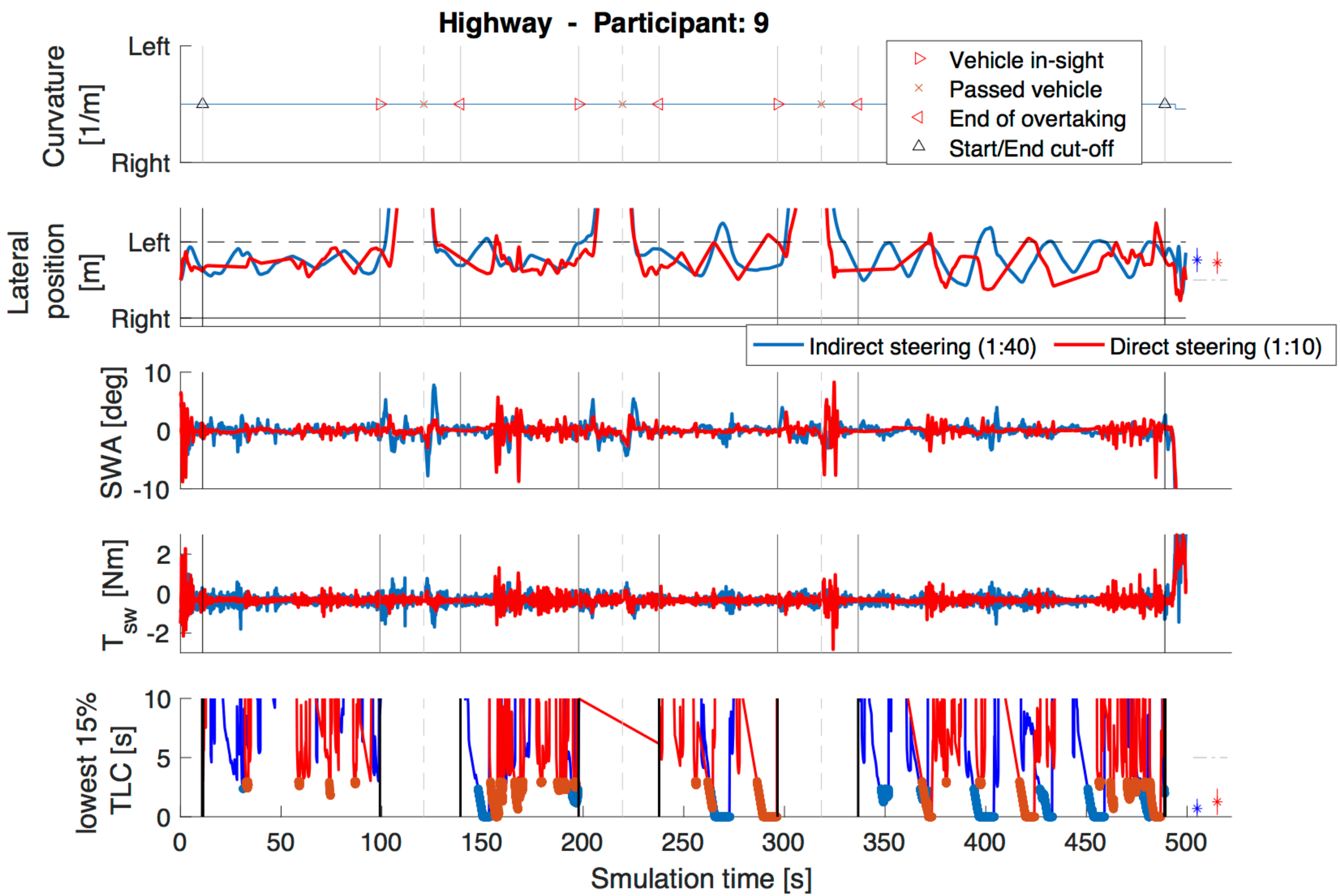


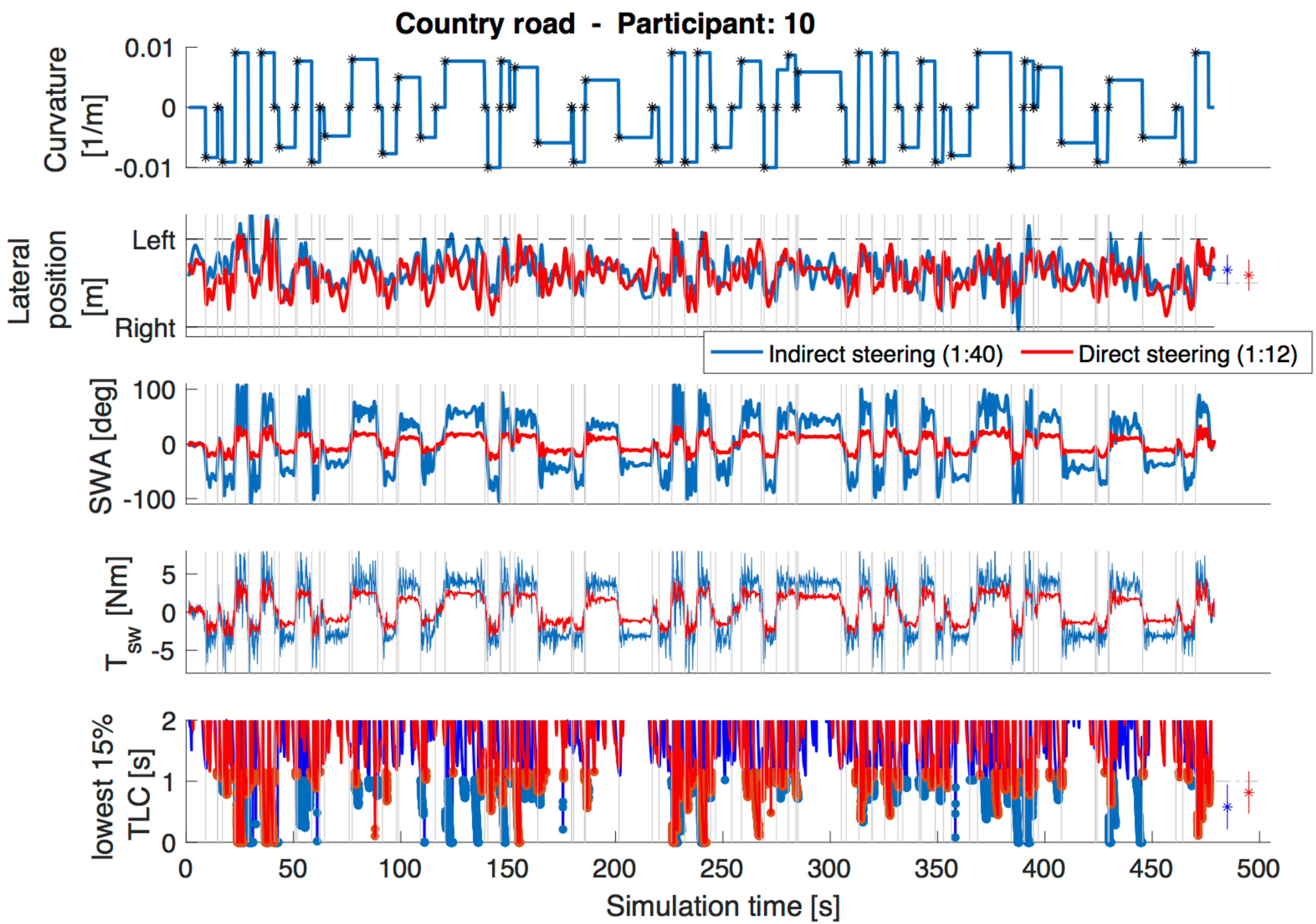
Country road - Participant: 8
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

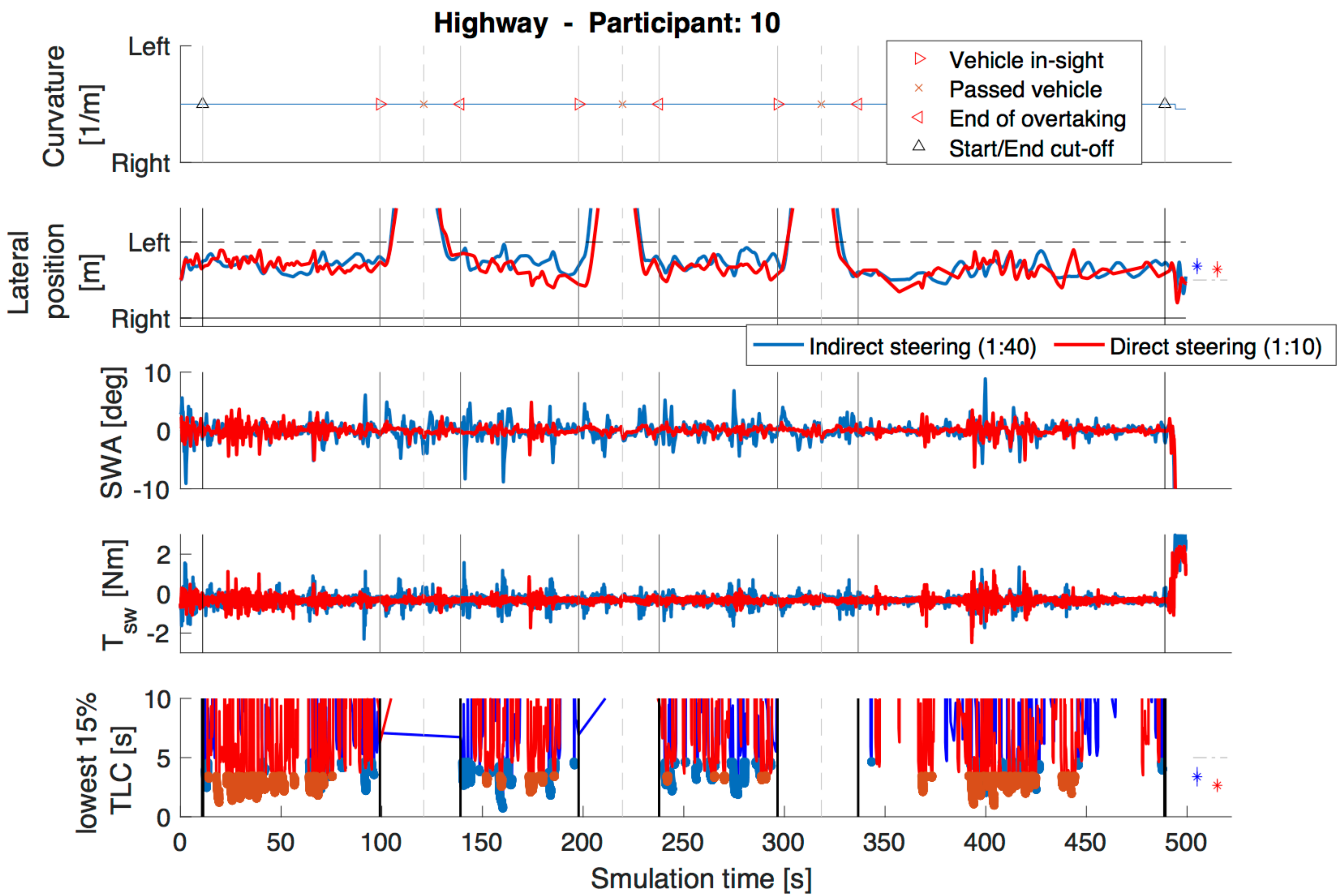


Highway - Participant: 8
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
T_{sw} [Nm]
lowest 15% TLC [s]
Smulation time [s]

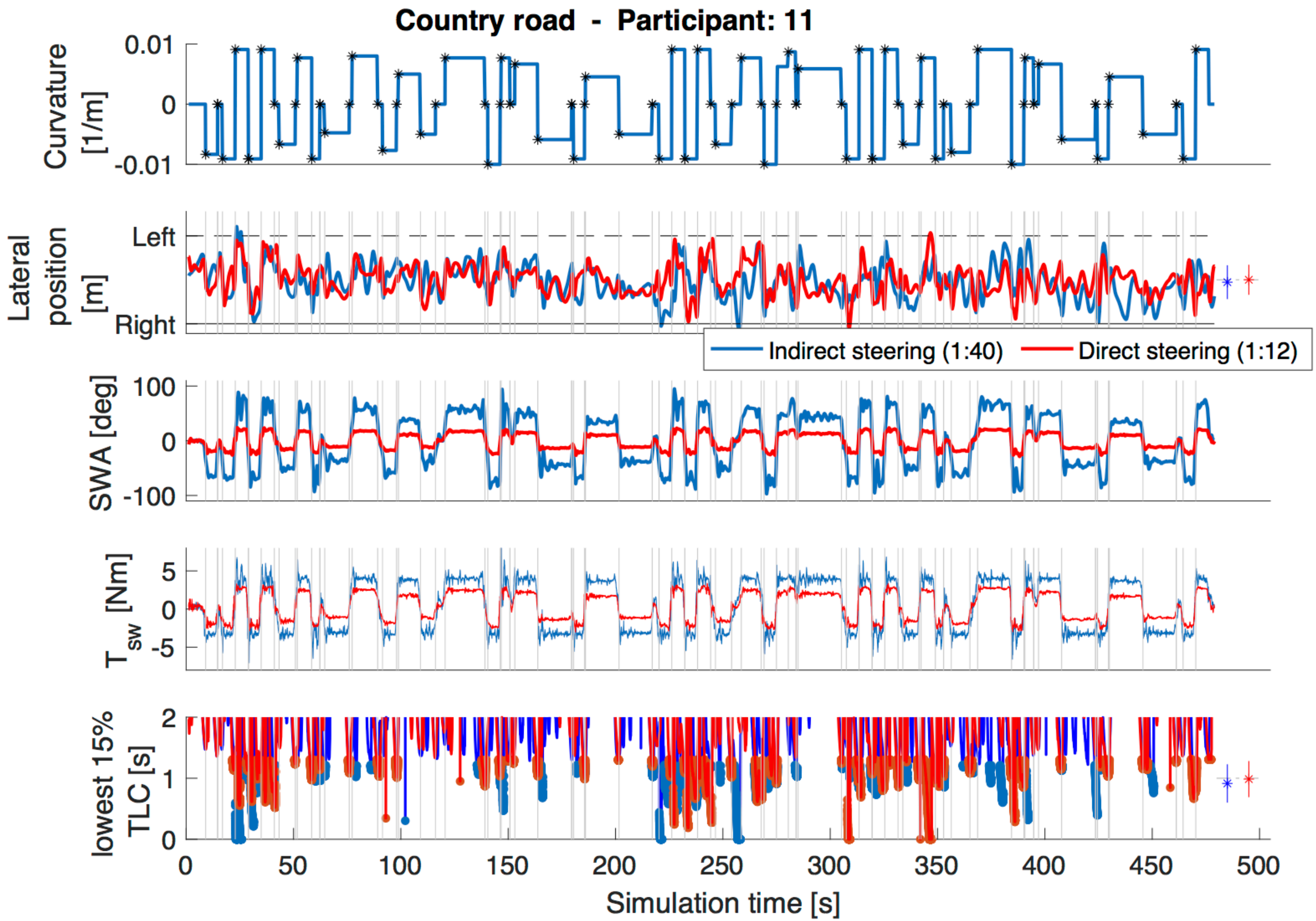

Country road - Participant: 9
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

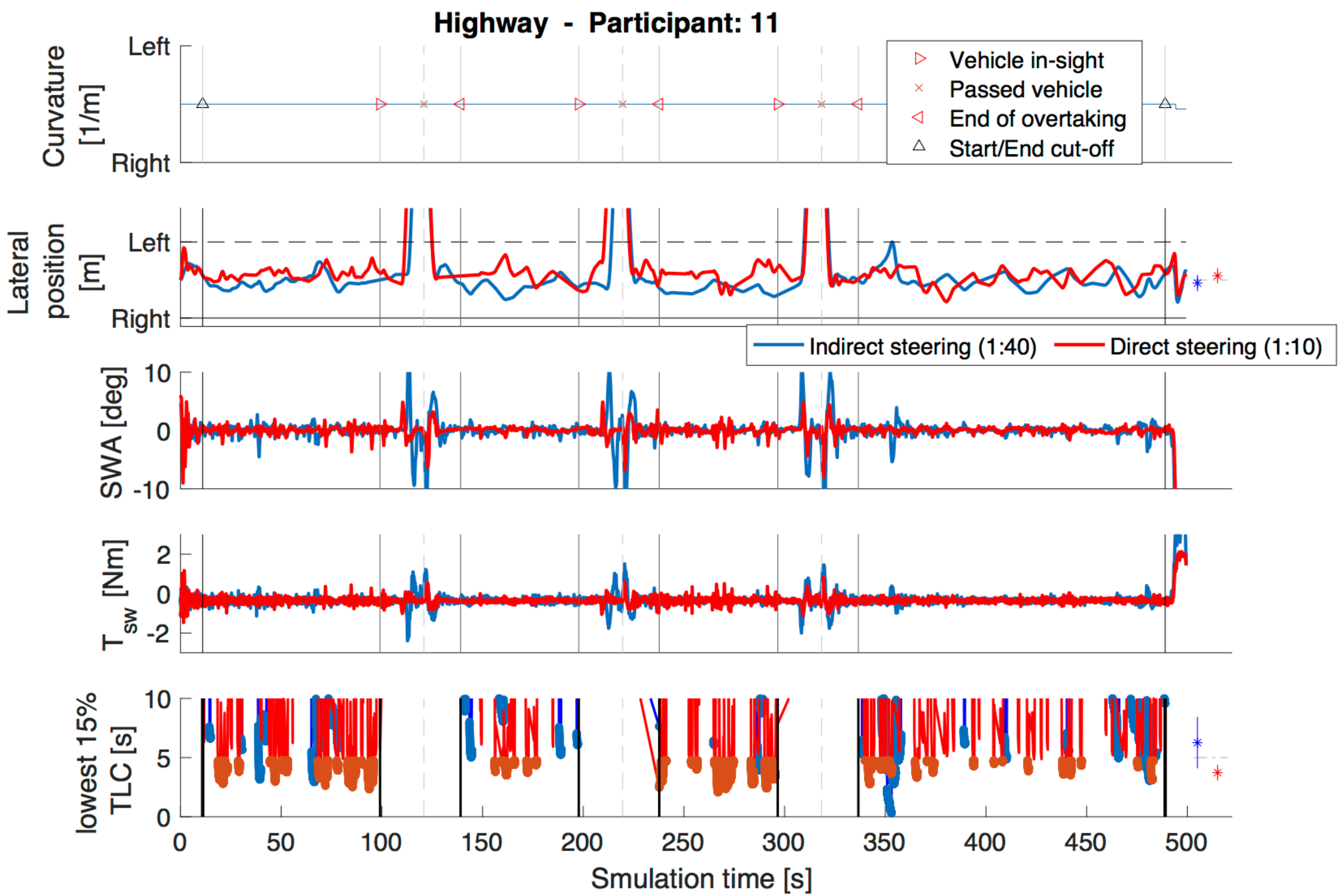

Highway - Participant: 9
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

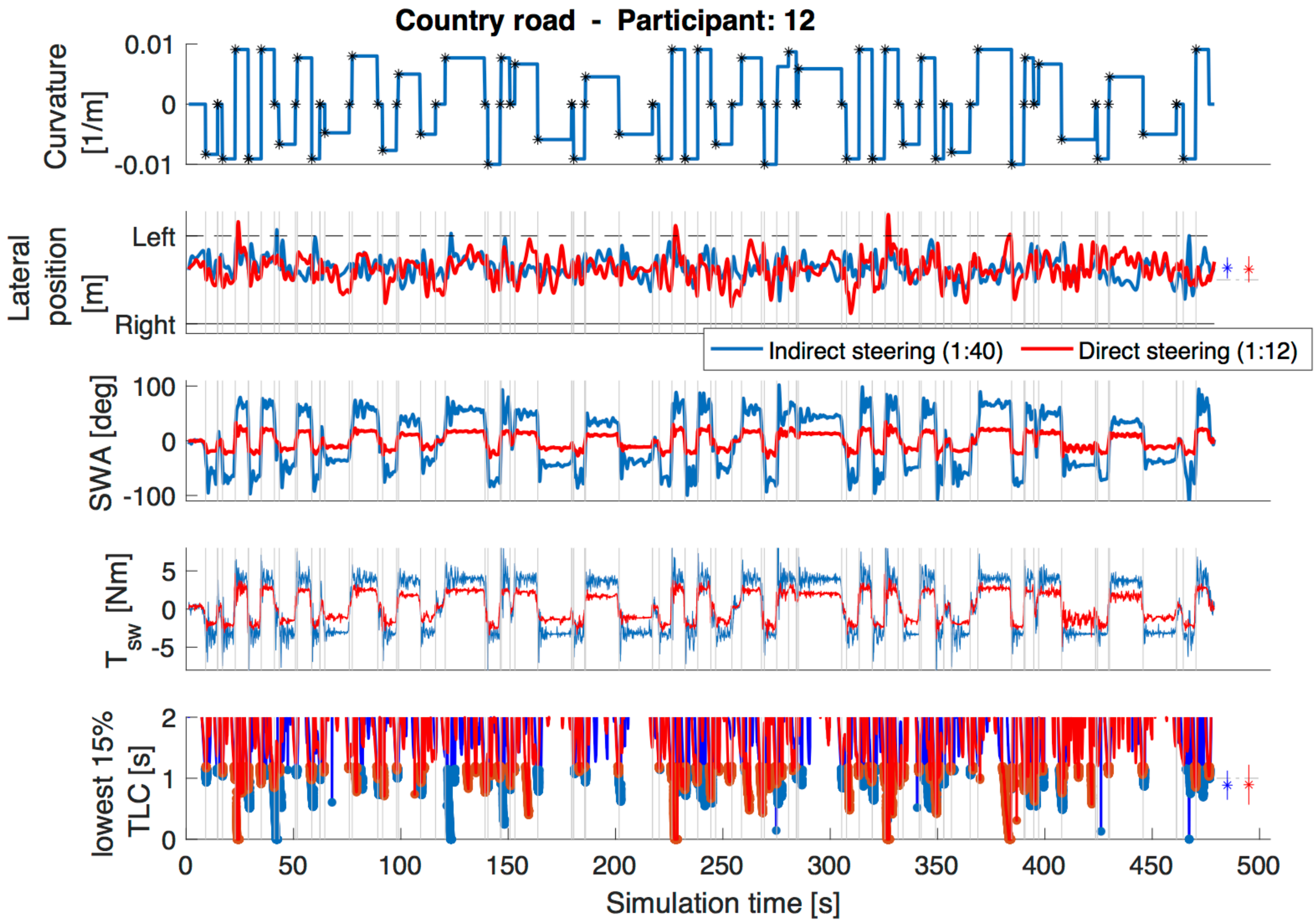

Country road - Participant: 10
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



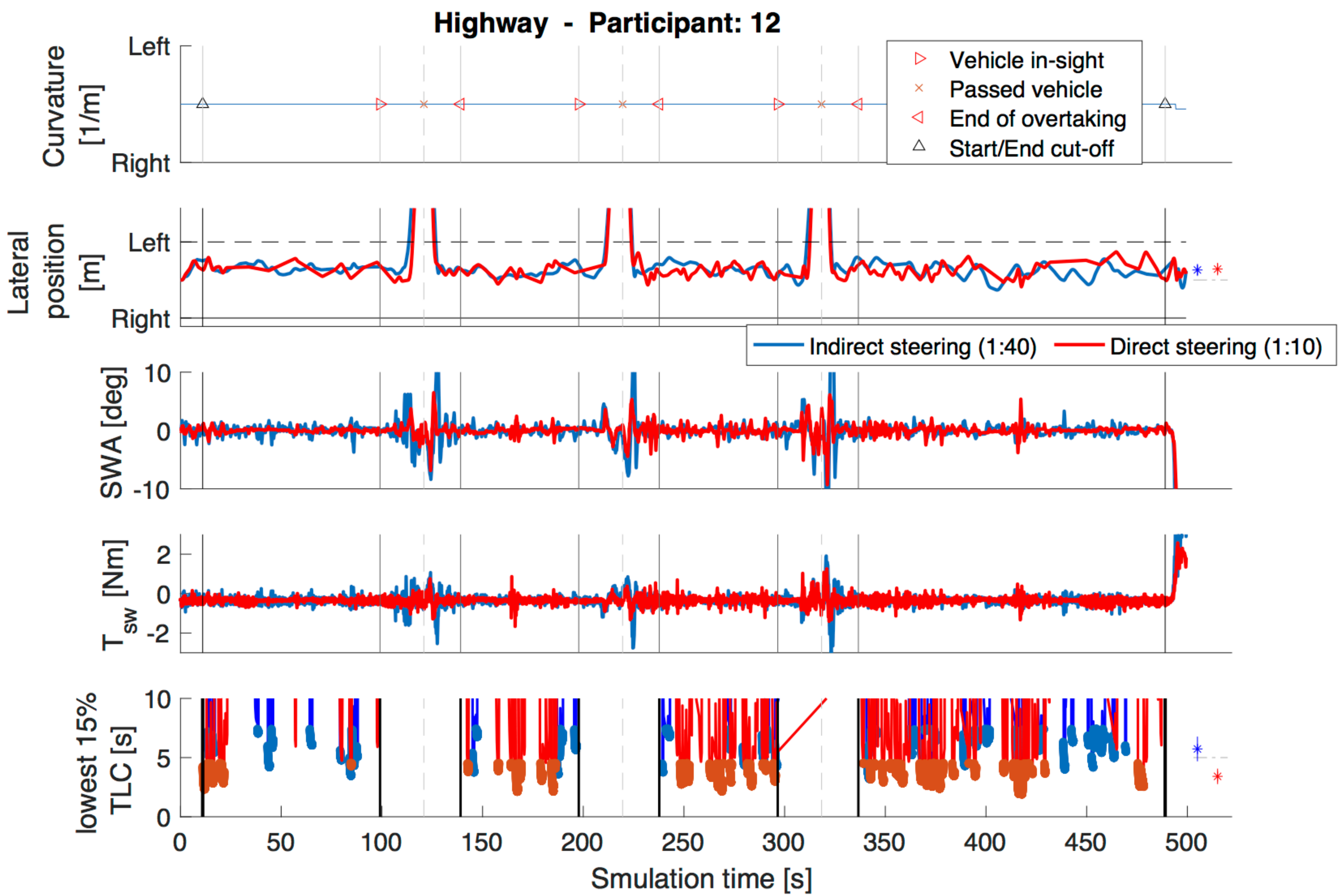
Highway - Participant: 10
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_sw [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]


Country road - Participant: 11
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_sw [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

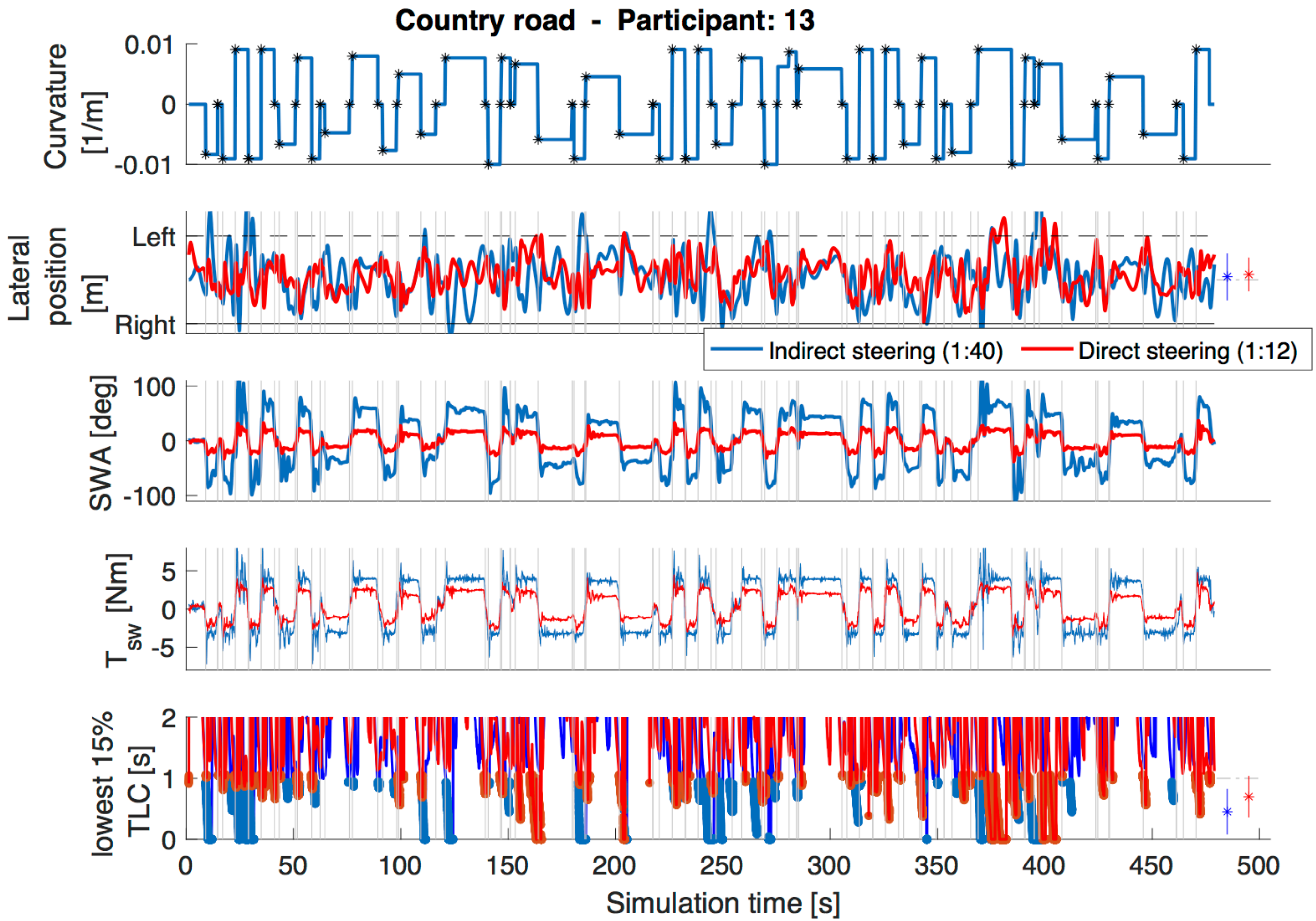

Highway - Participant: 11
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]



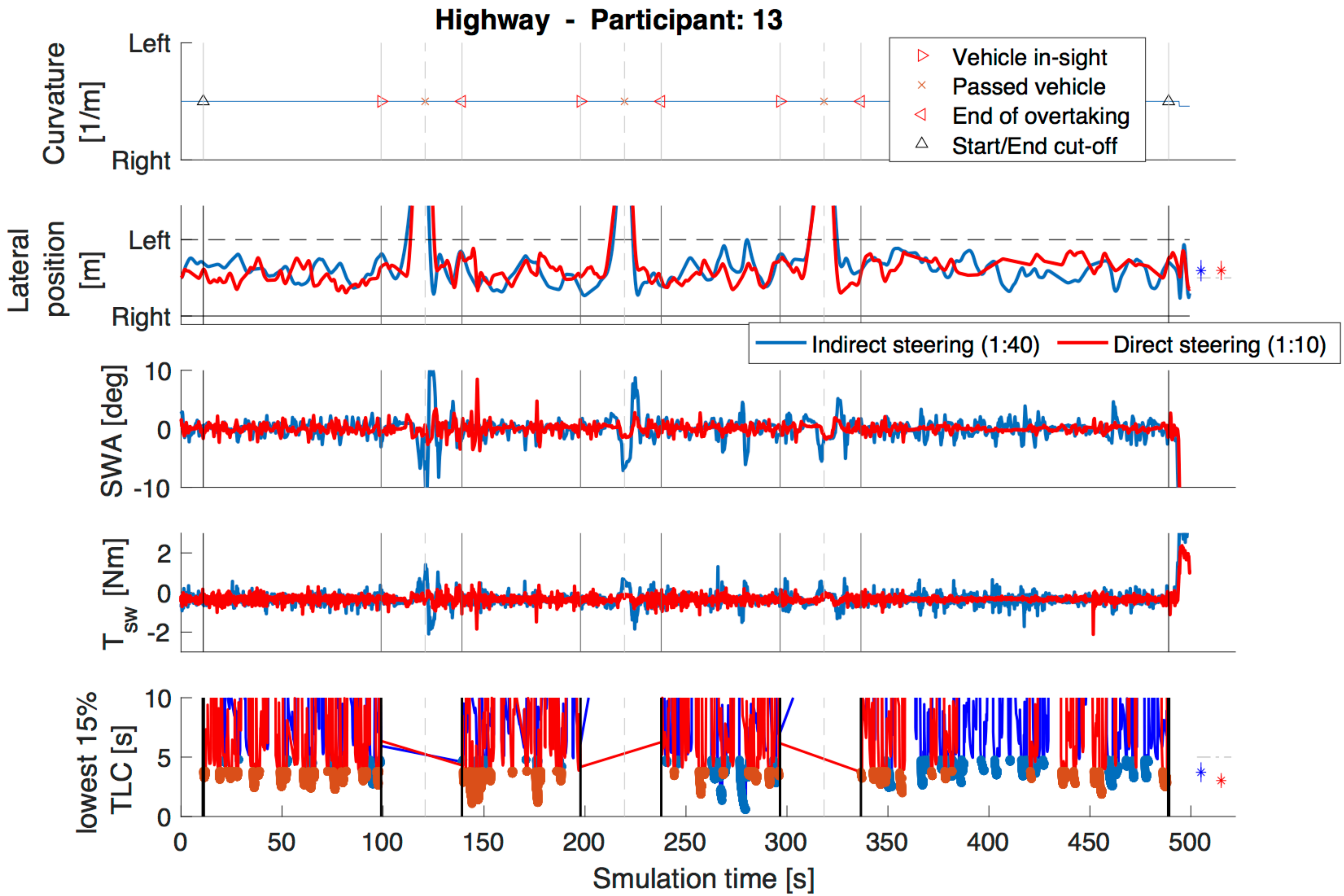
Country road - Participant: 12
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



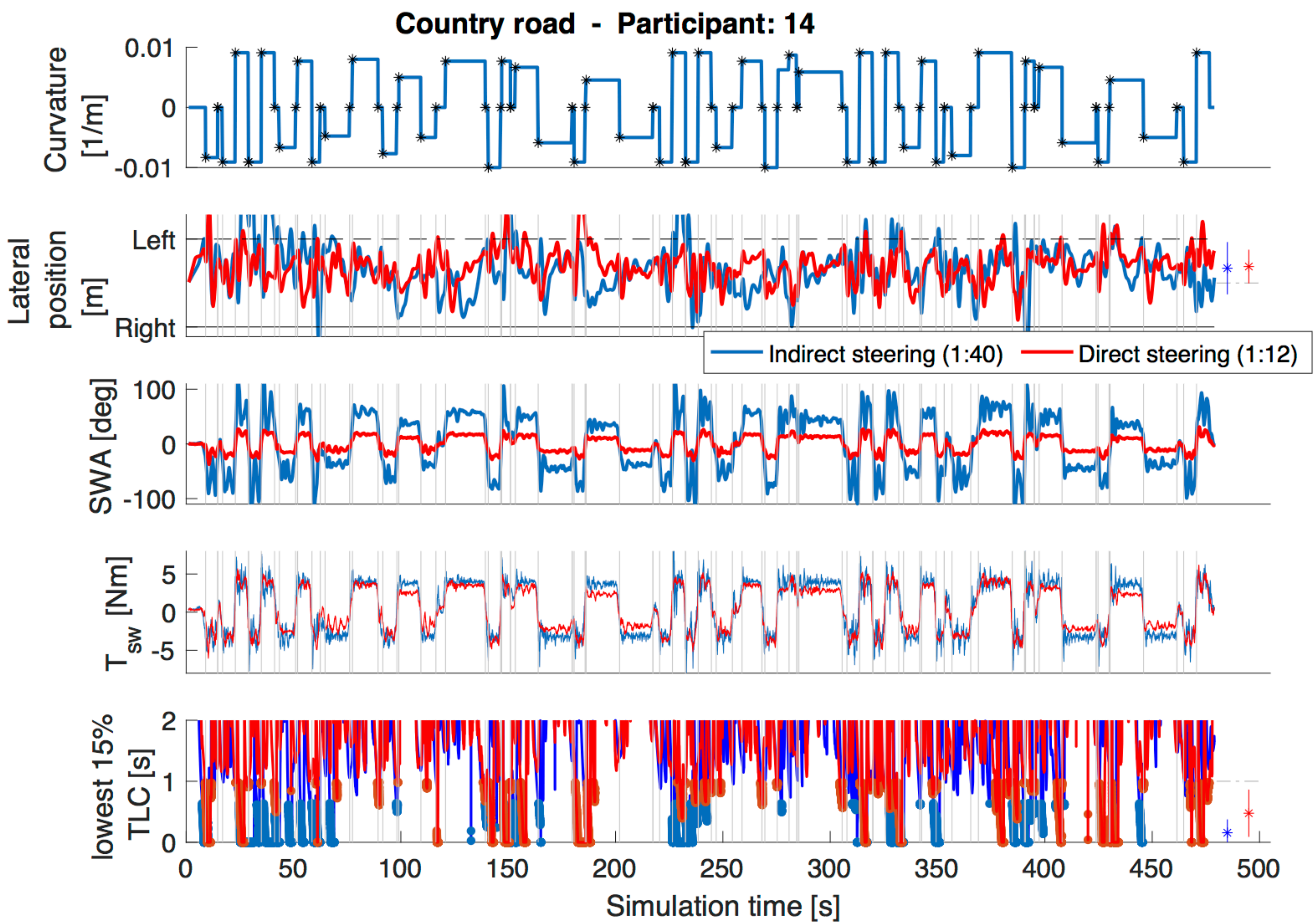
Highway - Participant: 12
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]



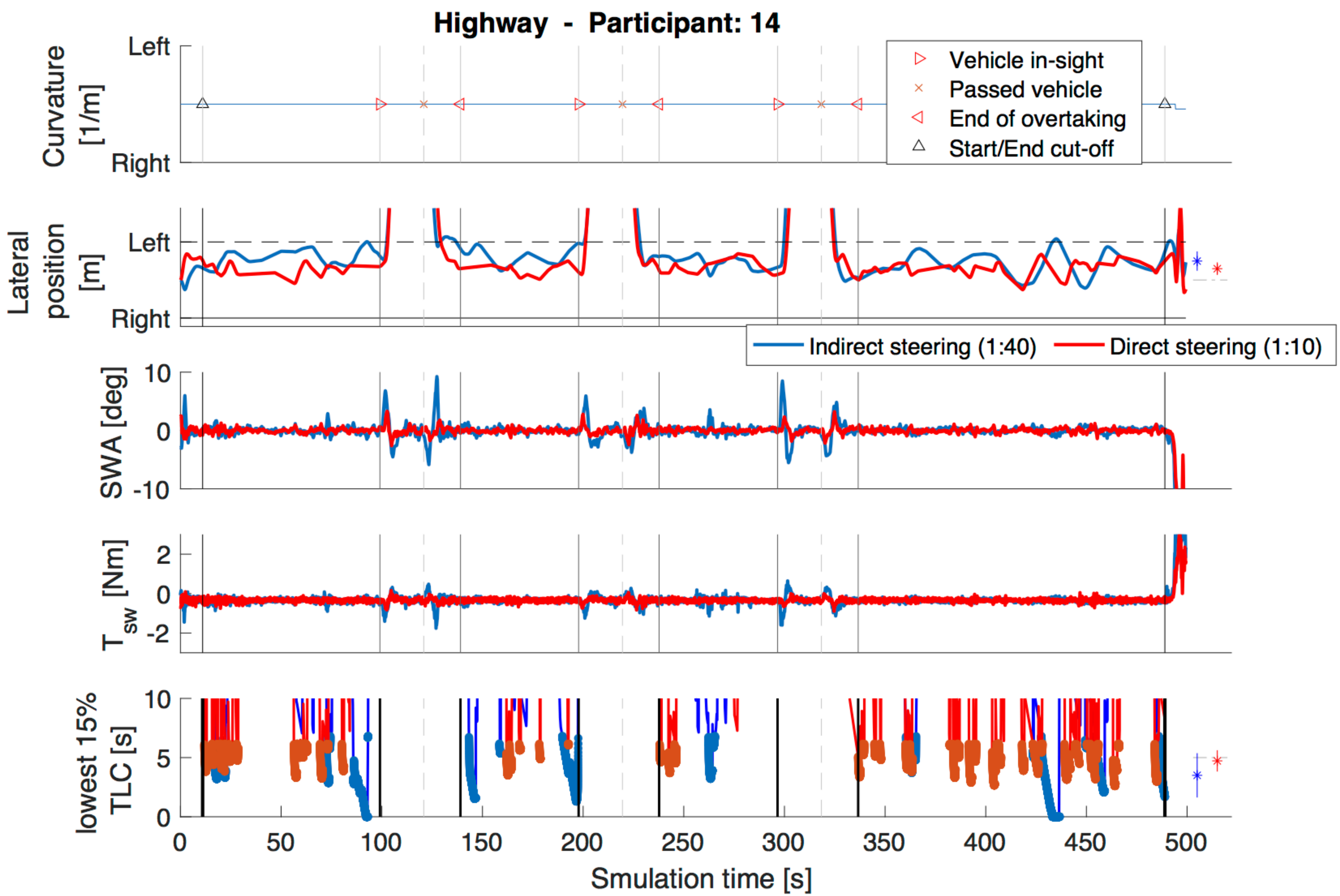
Country road - Participant: 13
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



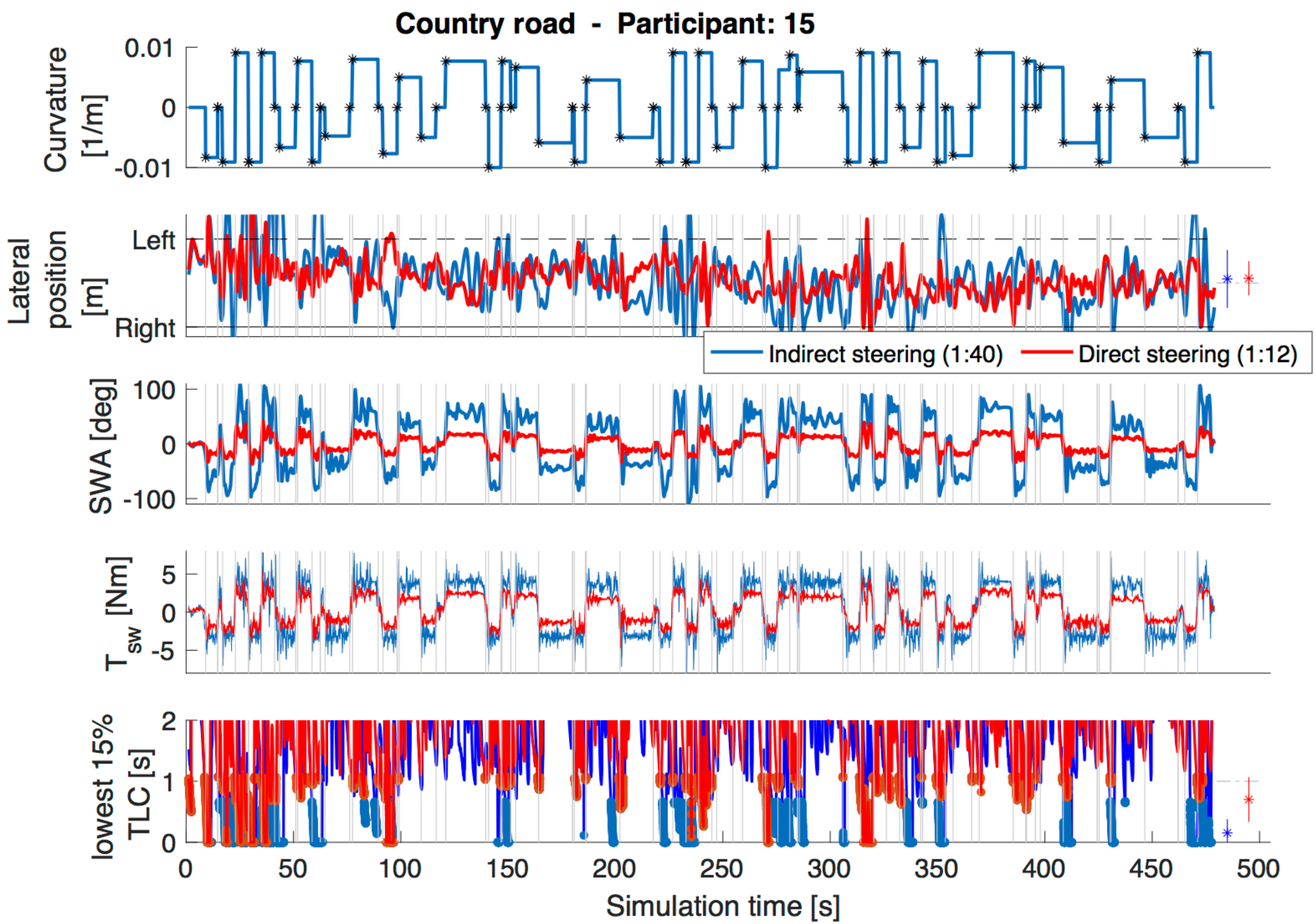
Highway - Participant: 13
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_sw [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

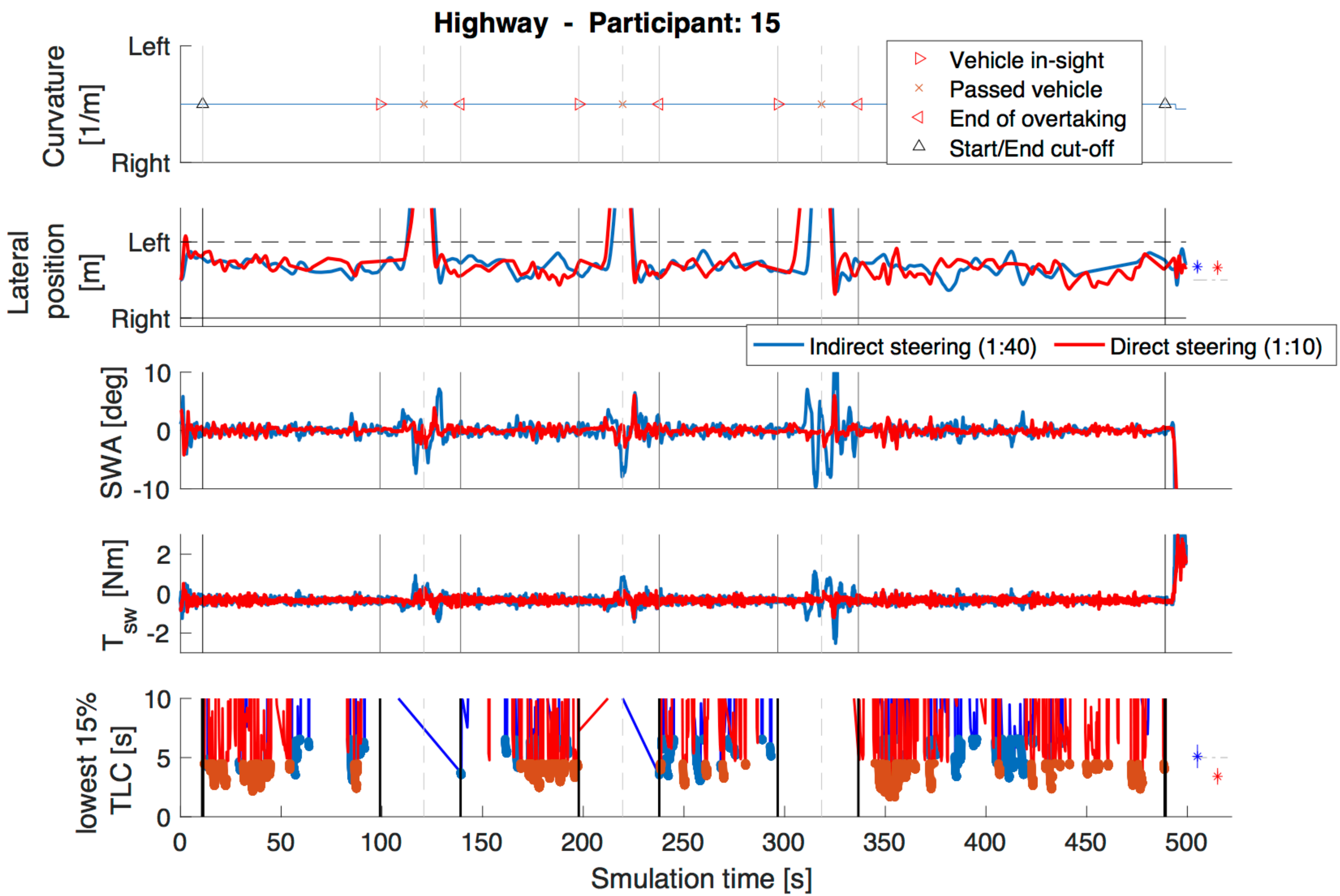


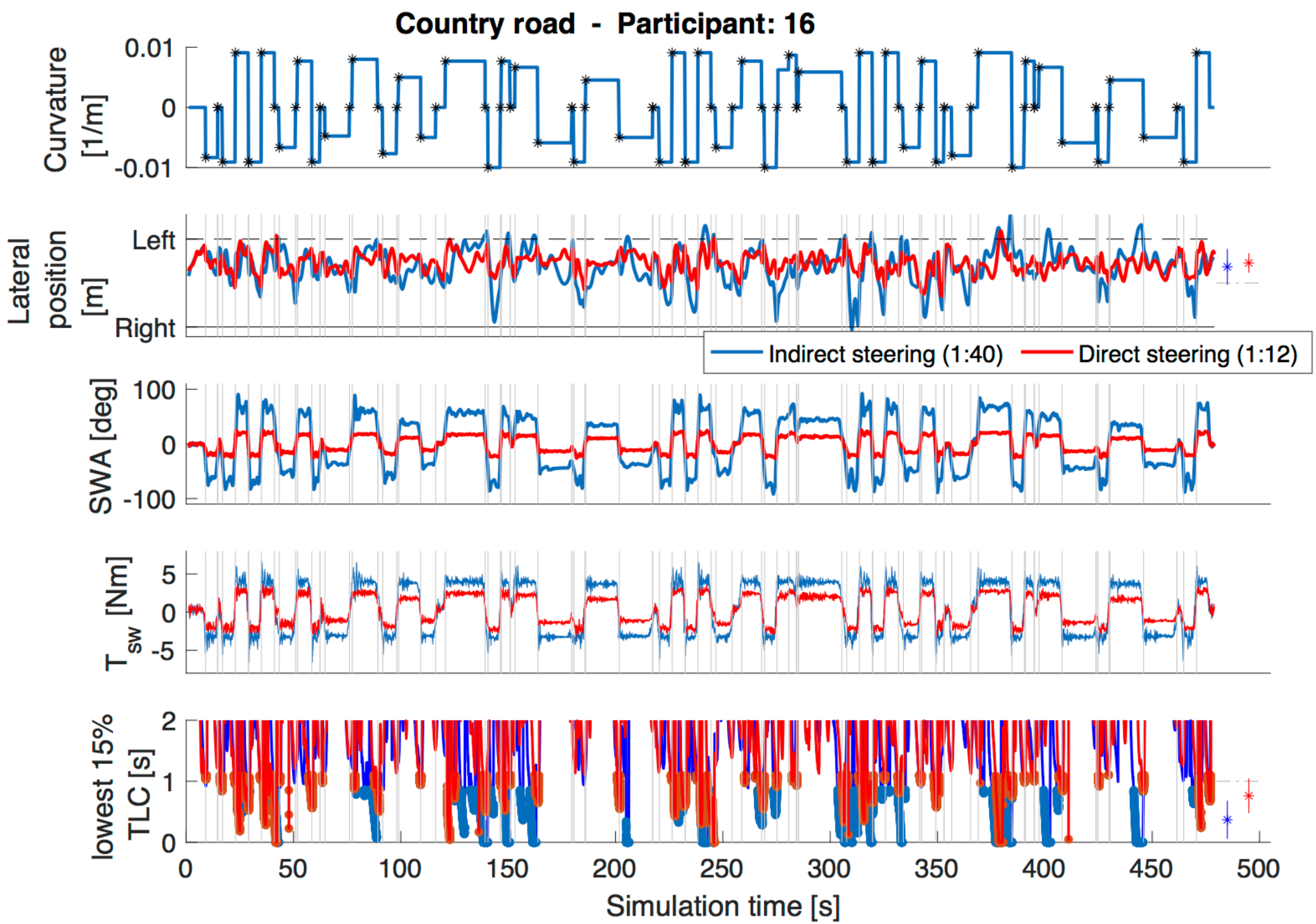
Country road - Participant: 14
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T sw [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

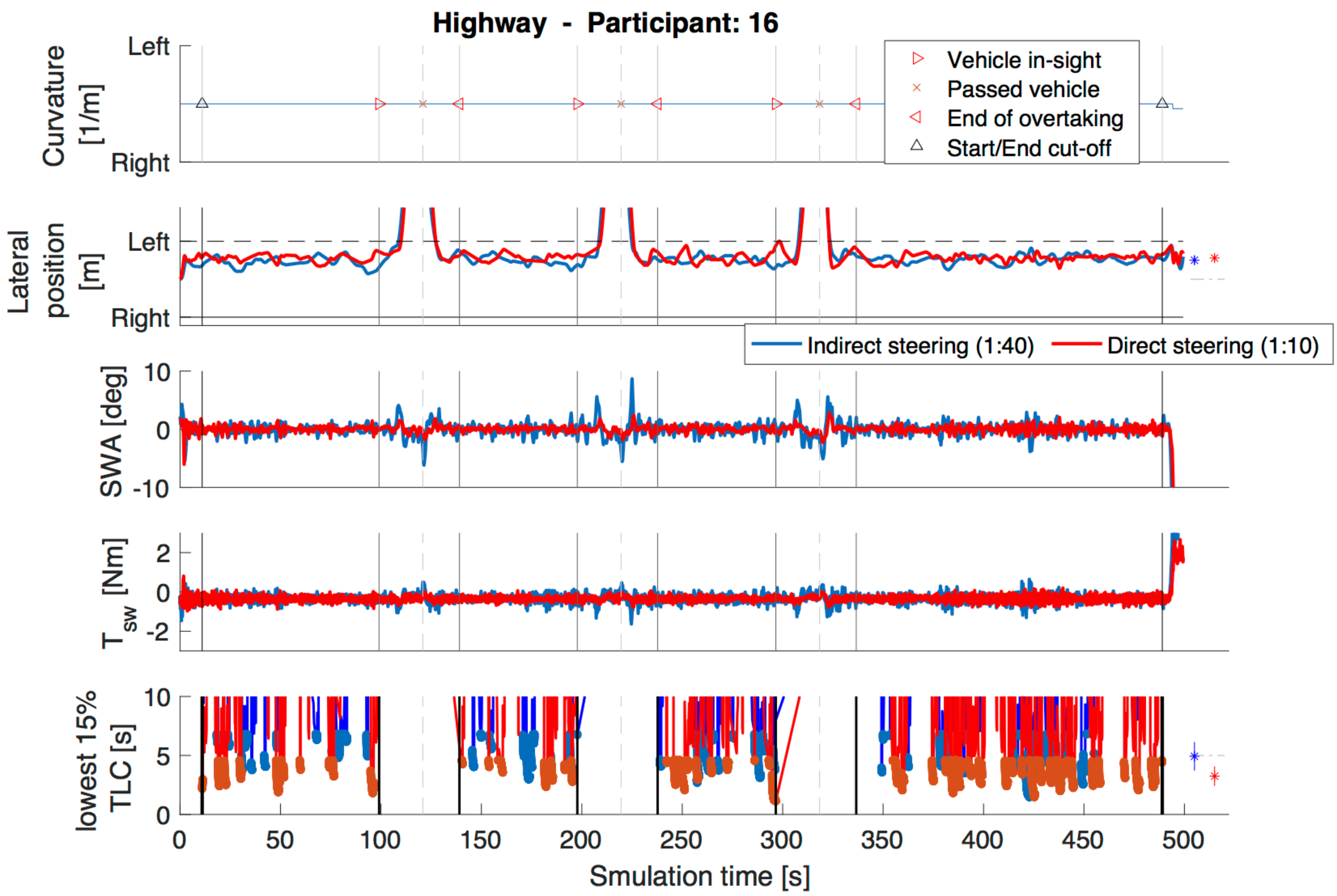


Highway - Participant: 14
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_sw [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

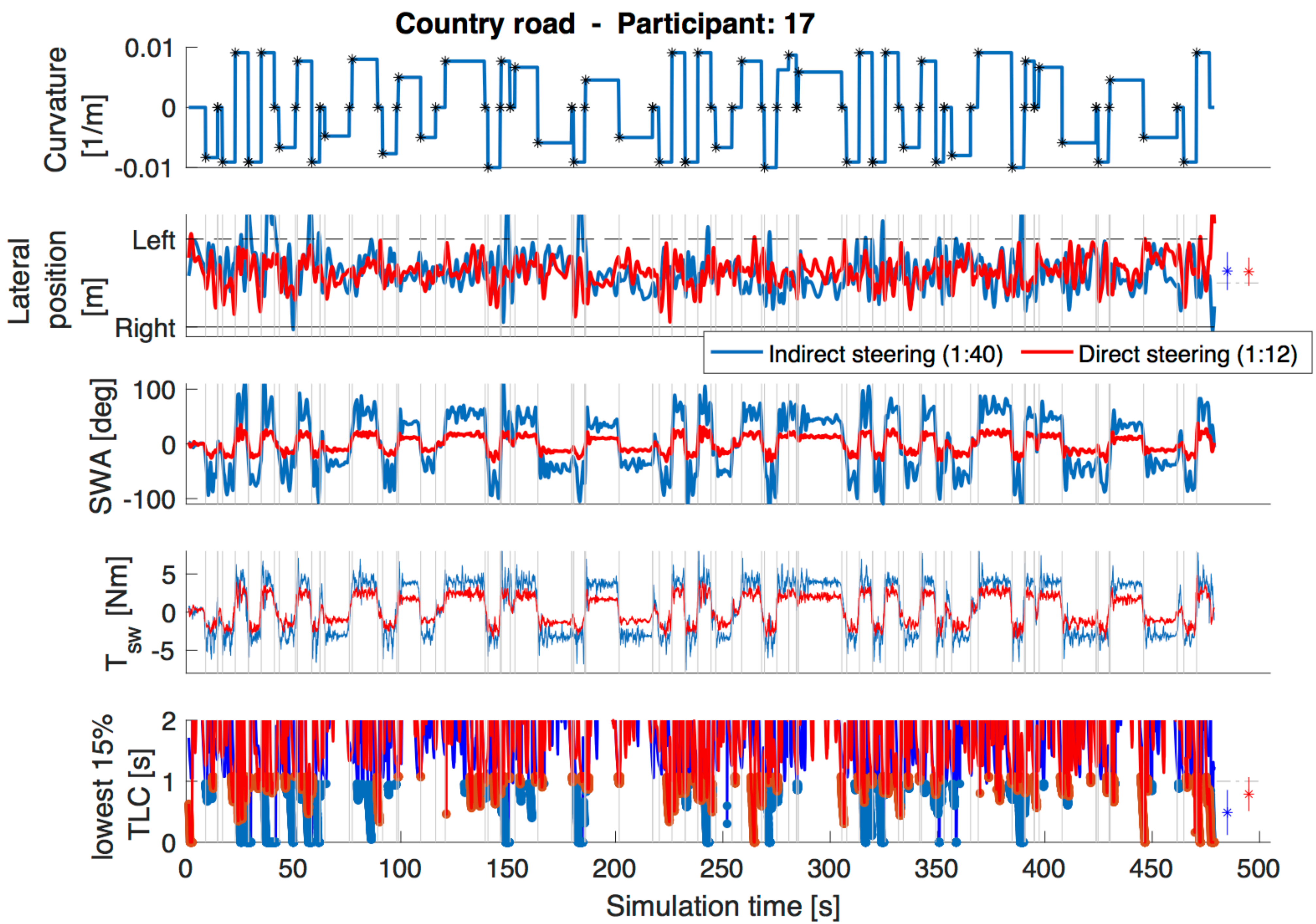

Country road - Participant: 15
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]


Highway - Participant: 15
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T sw [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

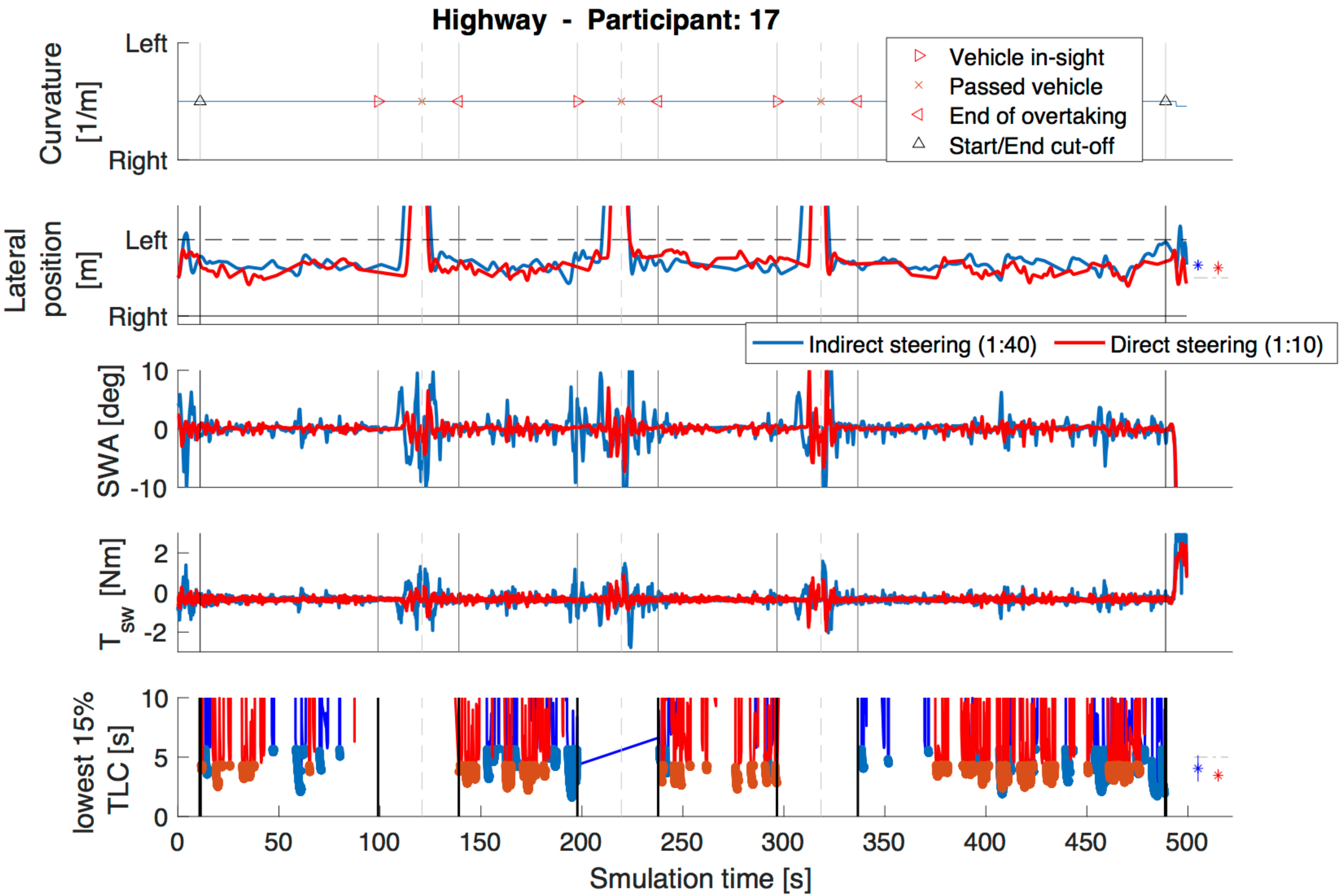

Country road - Participant: 16
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



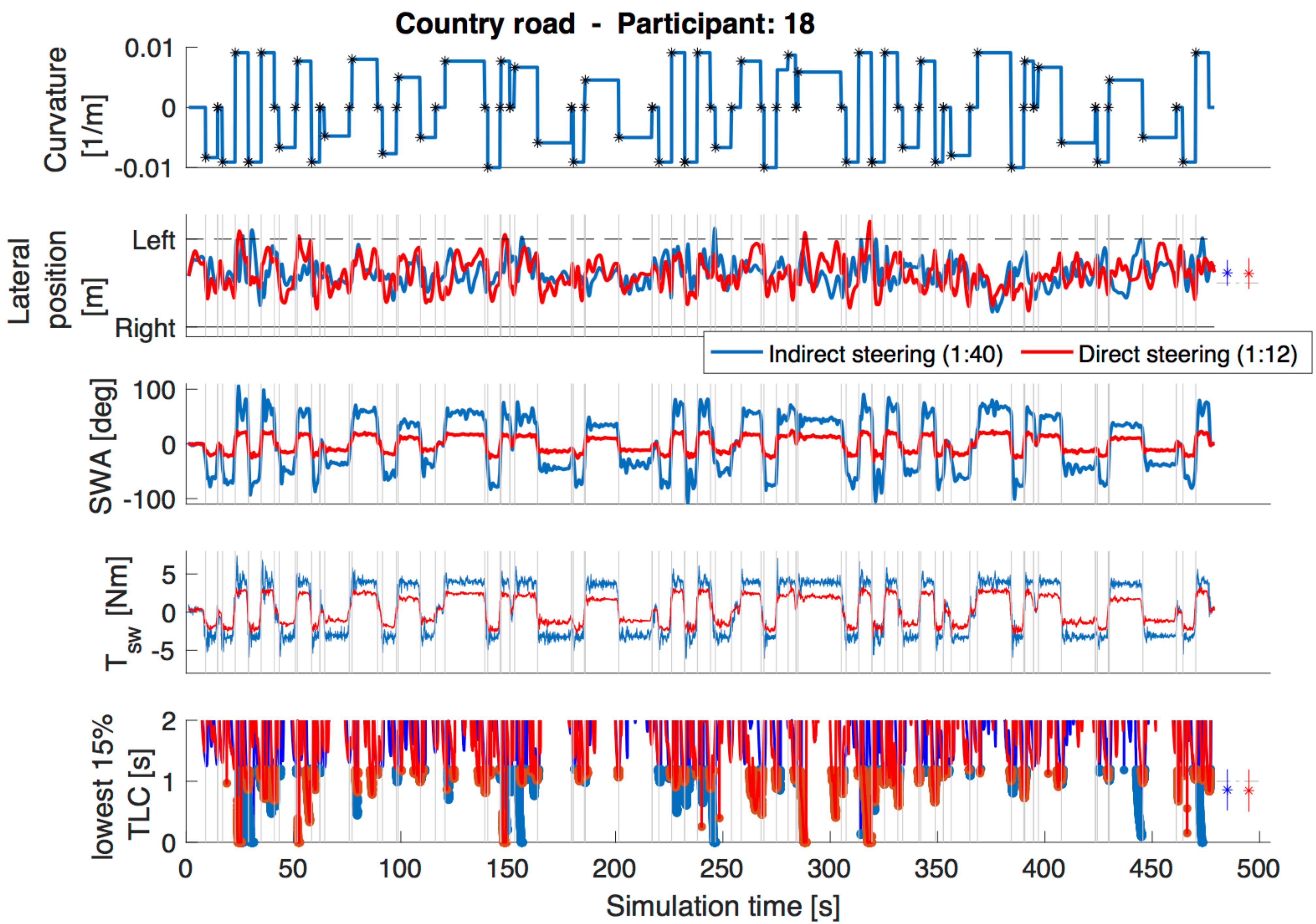
Highway - Participant: 16
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]



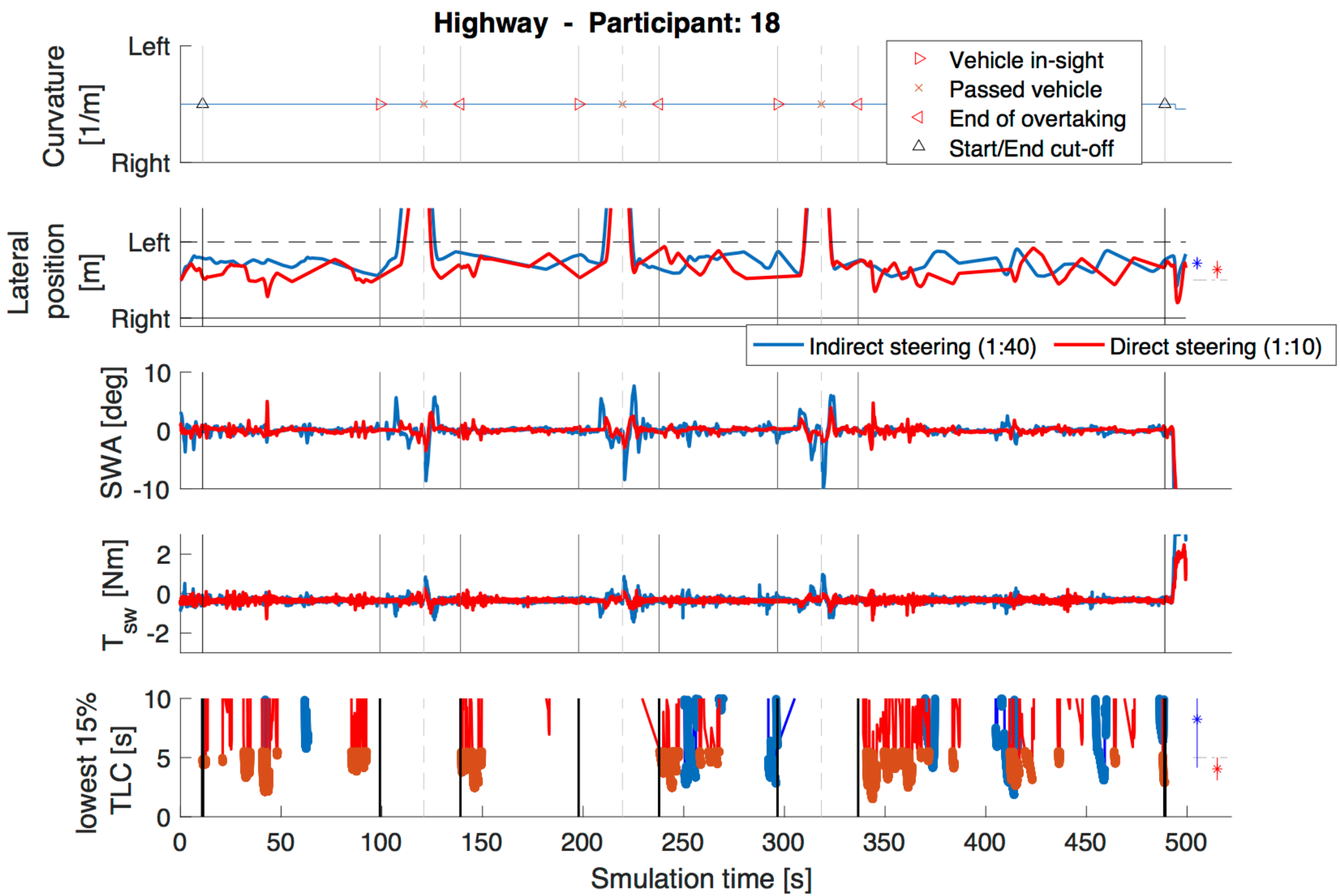
Country road - Participant: 17
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

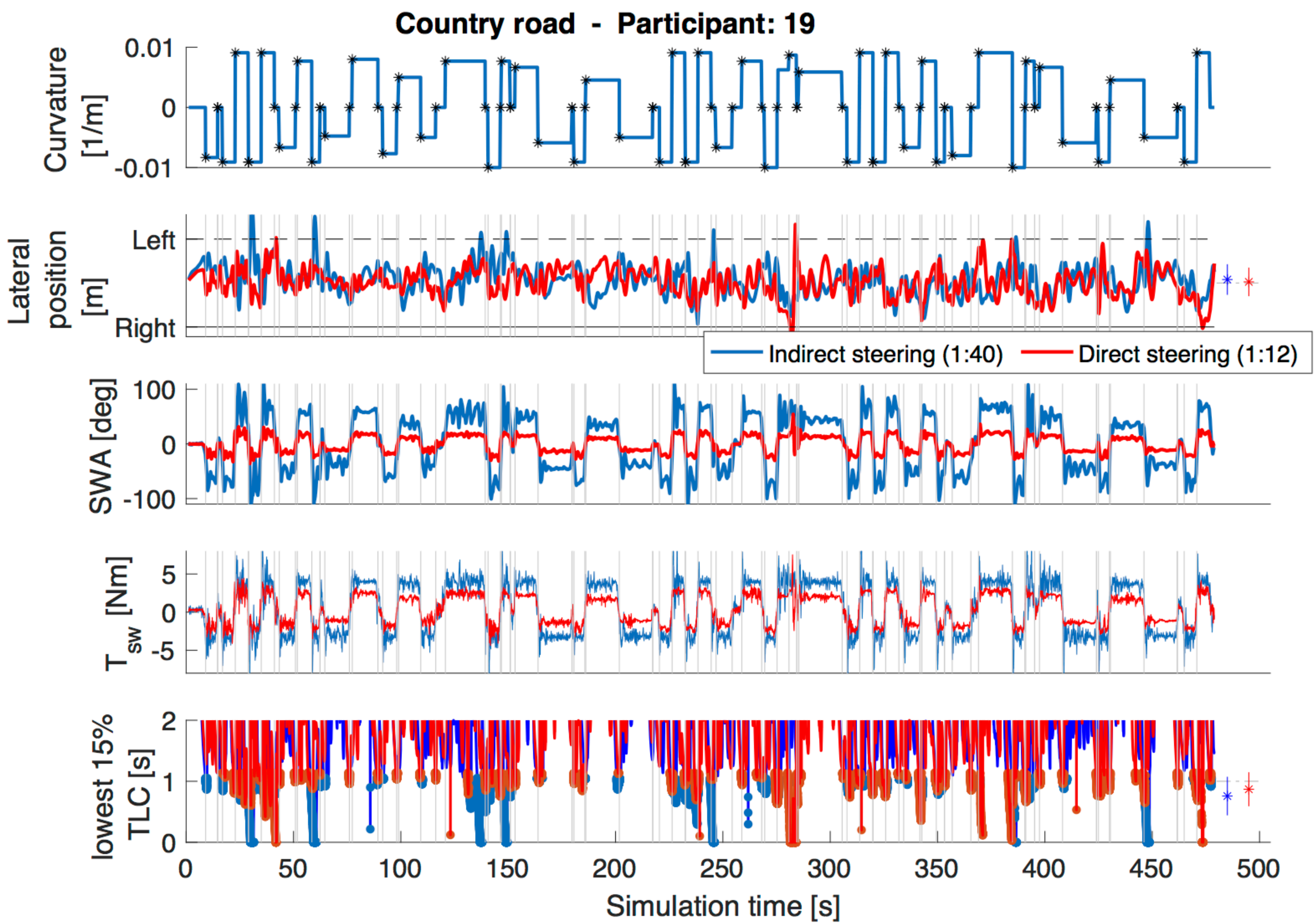


Highway - Participant: 17
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

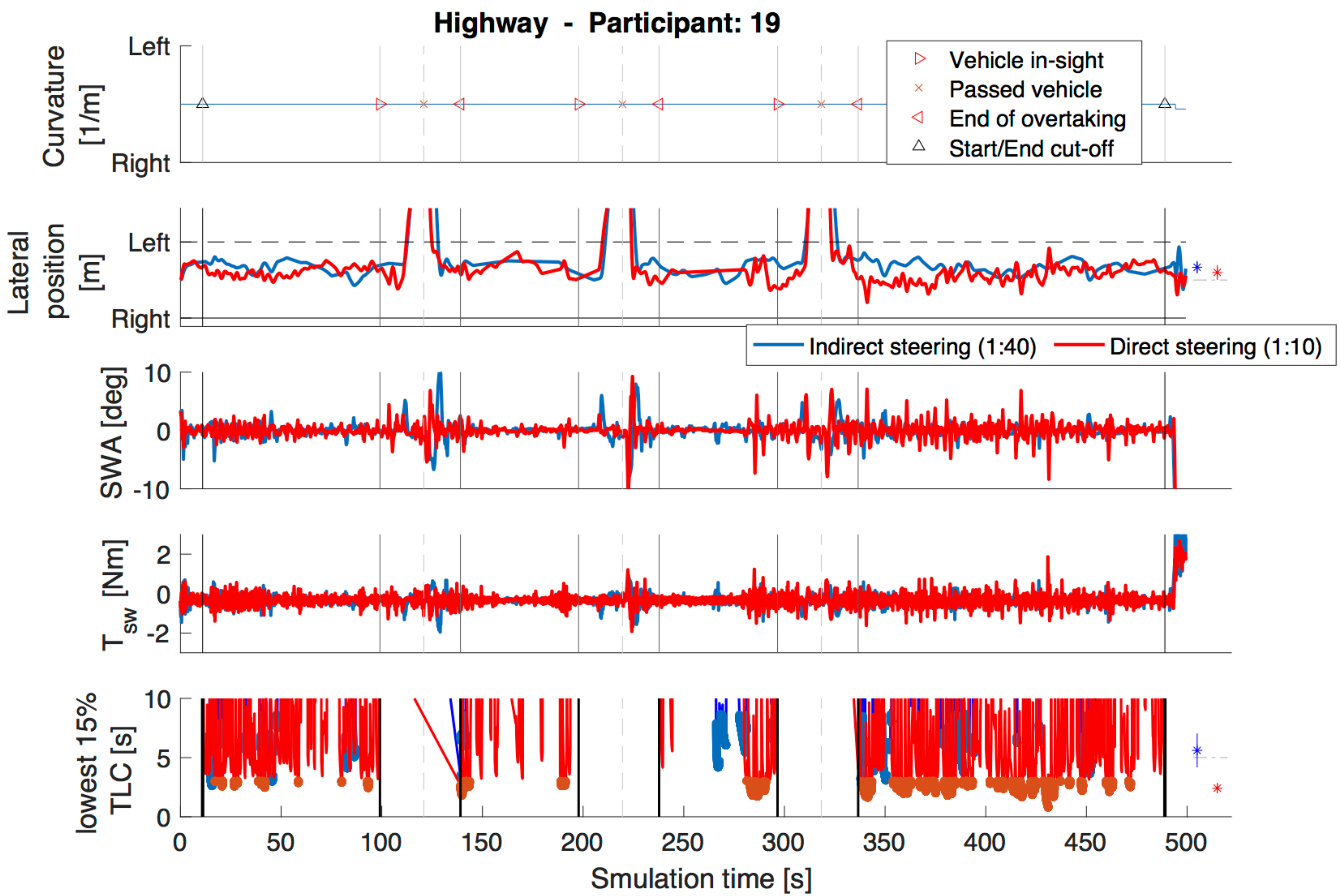


Country road - Participant: 18
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

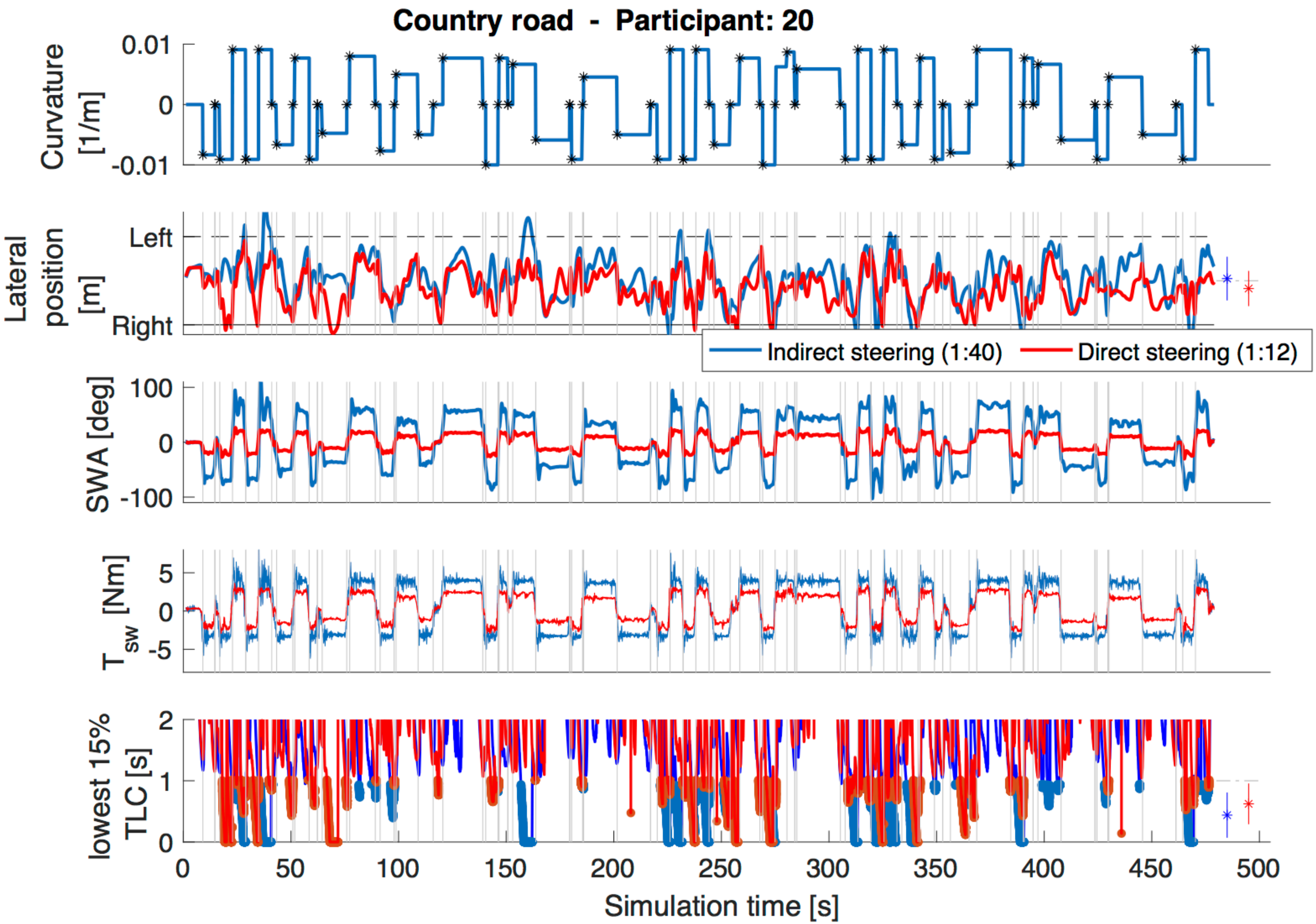

Highway - Participant: 18
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0 50 100 150 200 250 300 350 400 450 500
Smulation time [s]



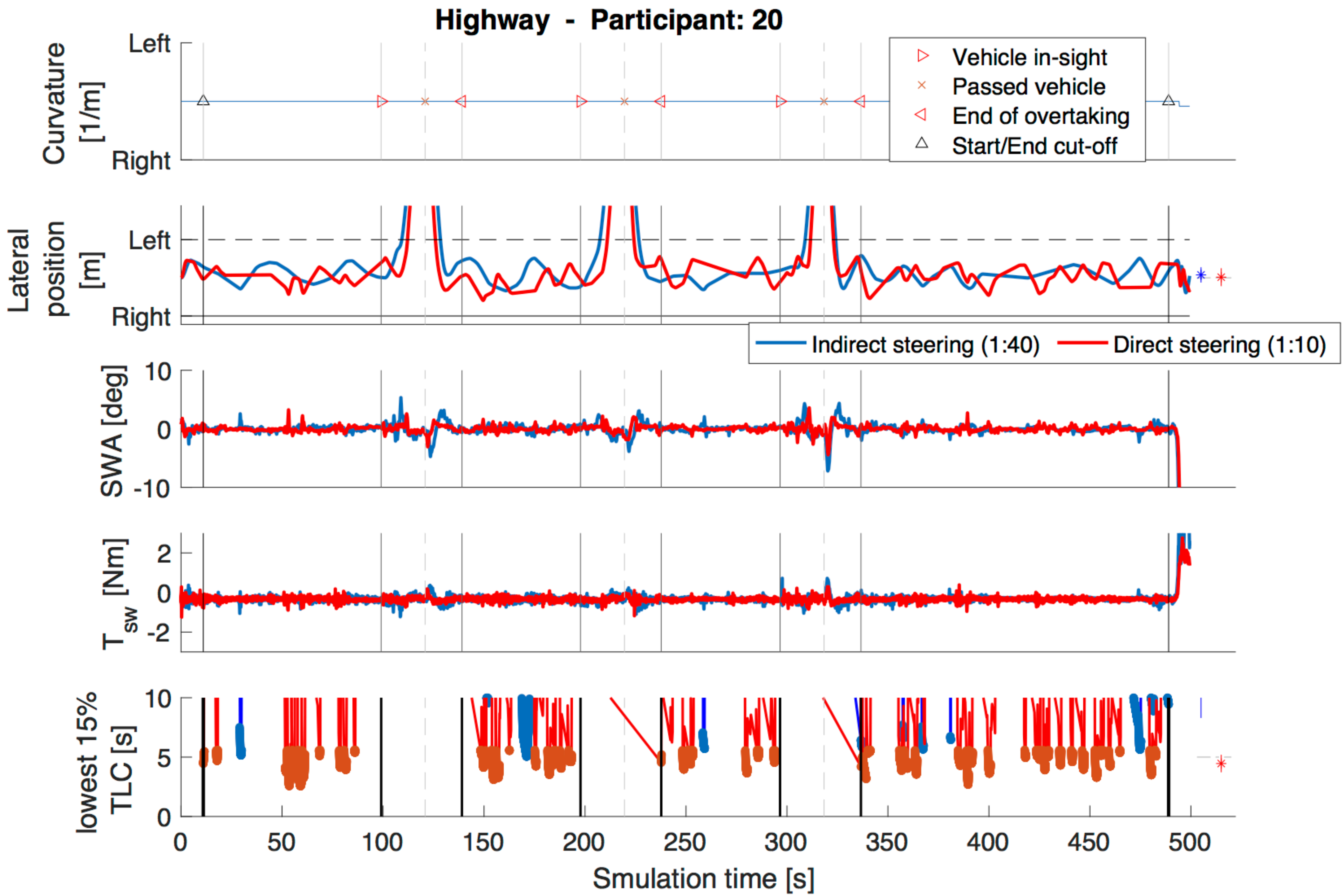
Country road - Participant: 19
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_sw [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



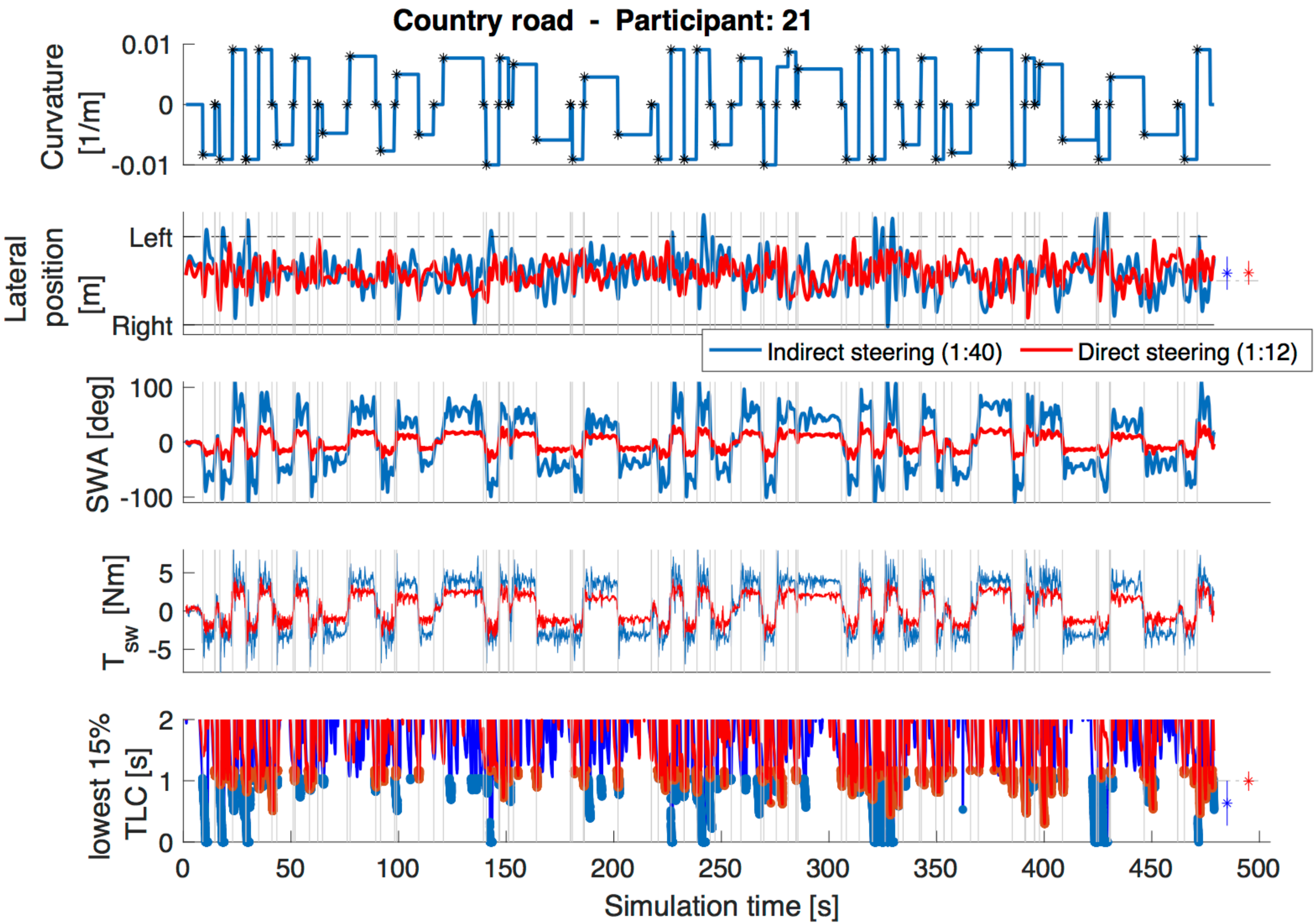
Highway - Participant: 19
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
T sw [Nm]
lowest 15% TLC [s]
Smulation time [s]



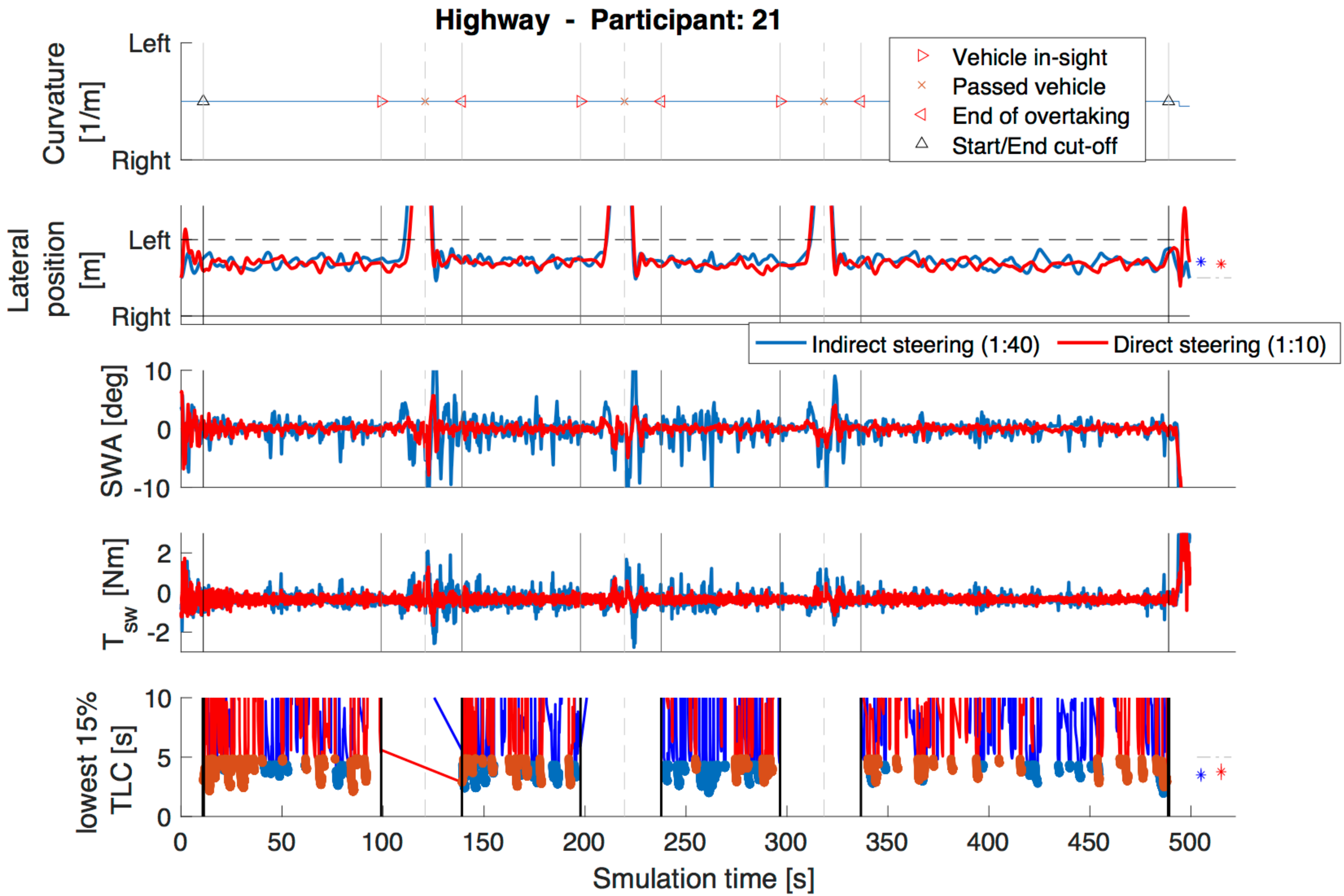
Country road - Participant: 20
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_sw [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]

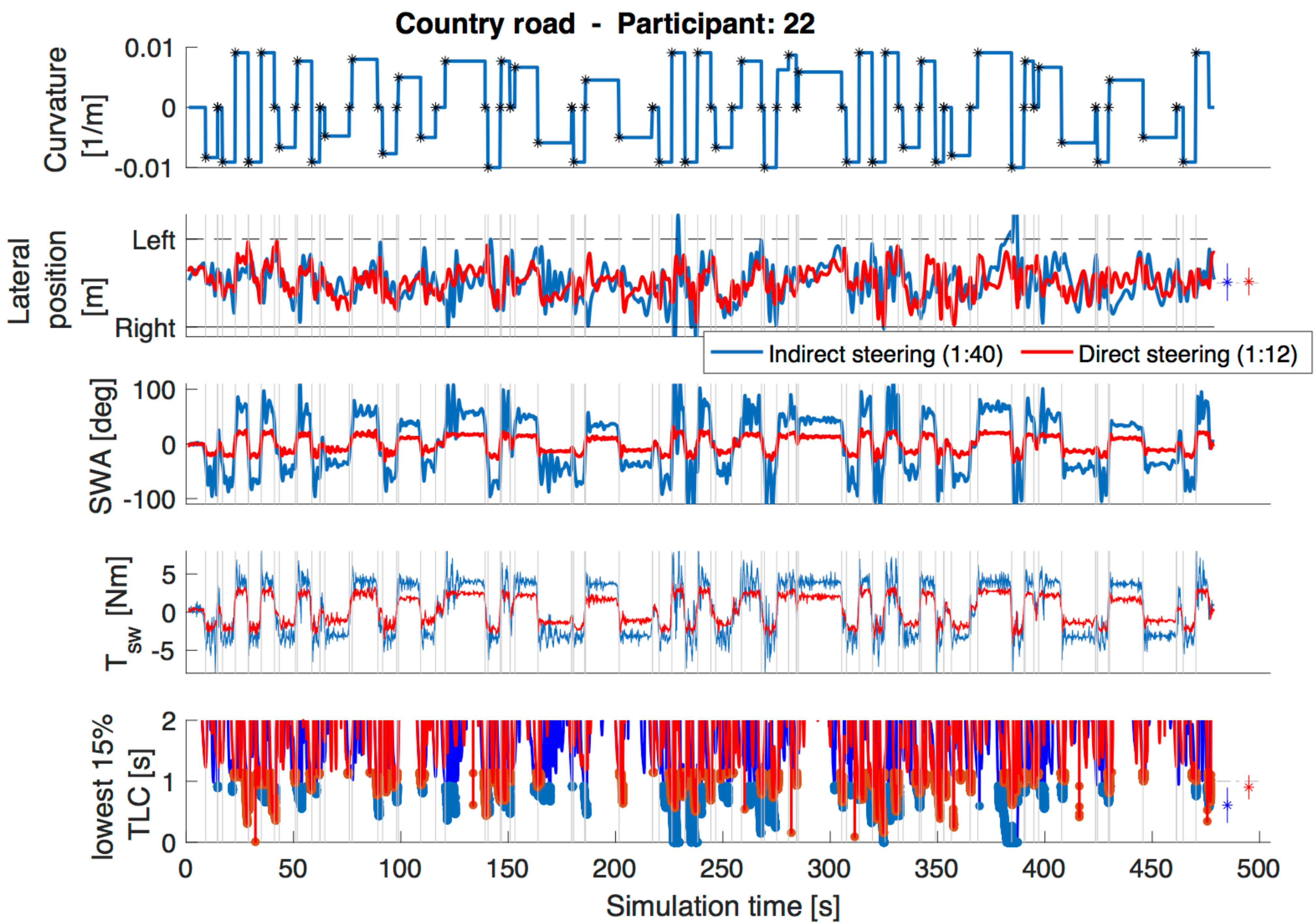


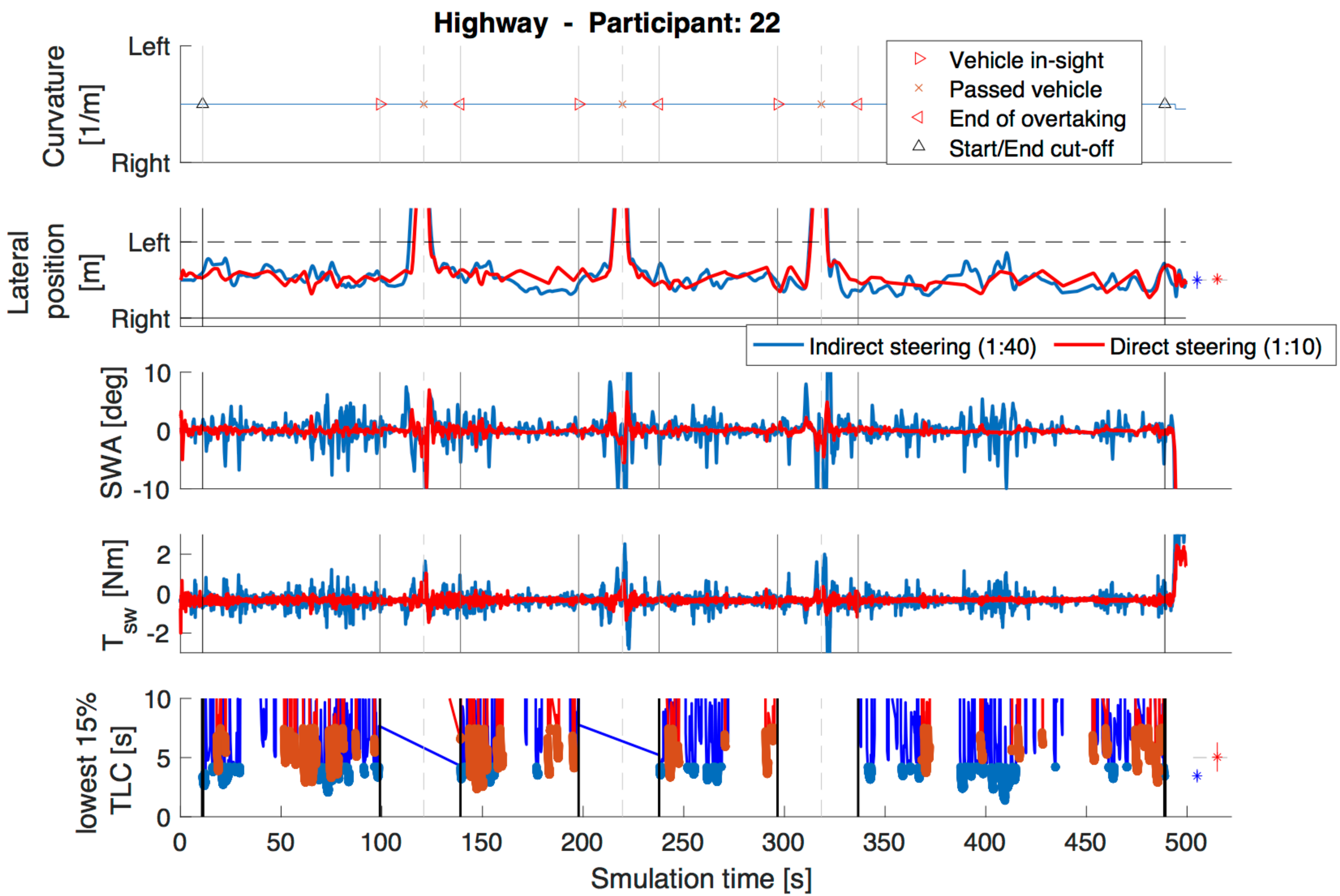
Highway - Participant: 20
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T sw [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]



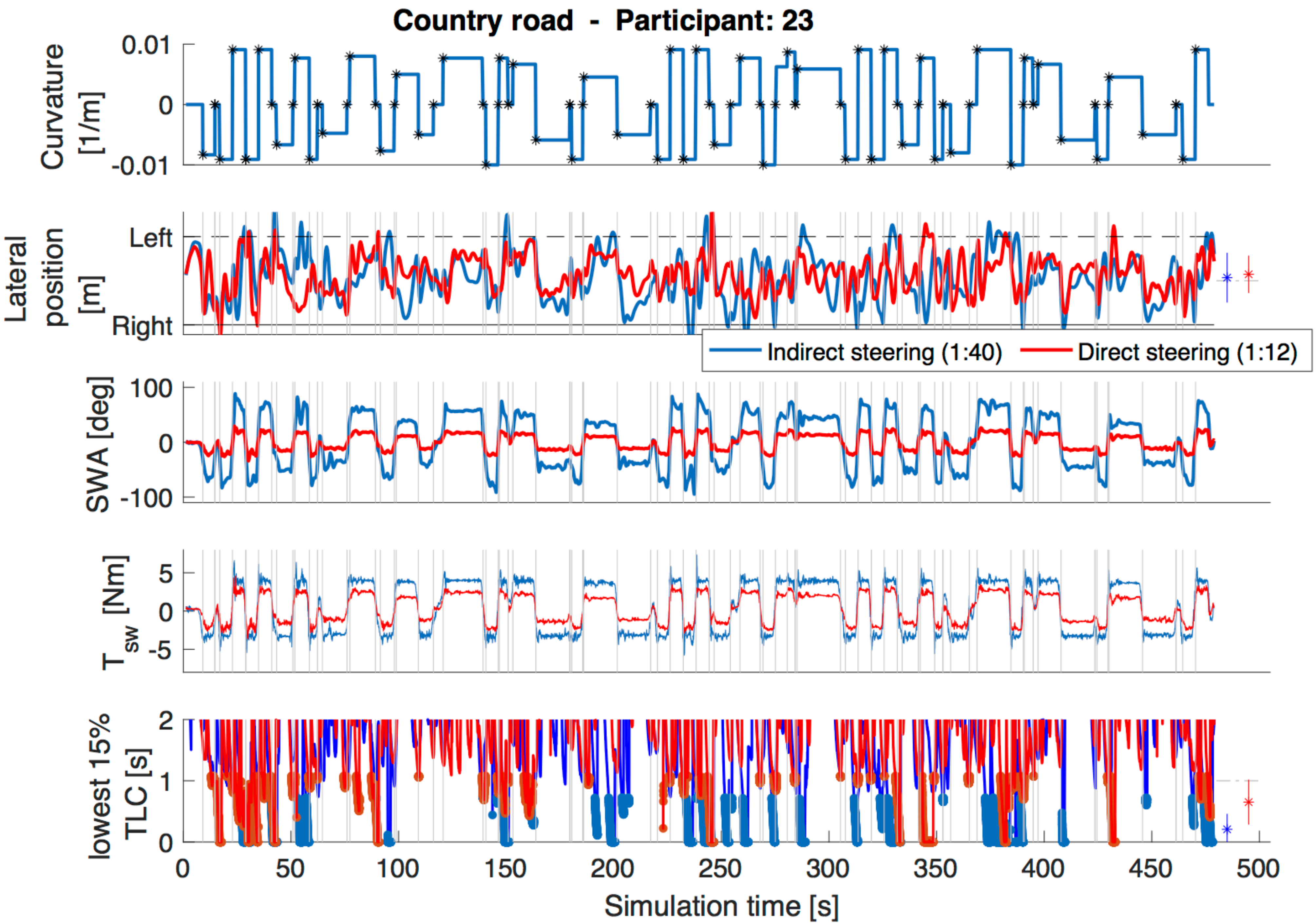
Country road - Participant: 21
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]


Highway - Participant: 21
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T sw [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

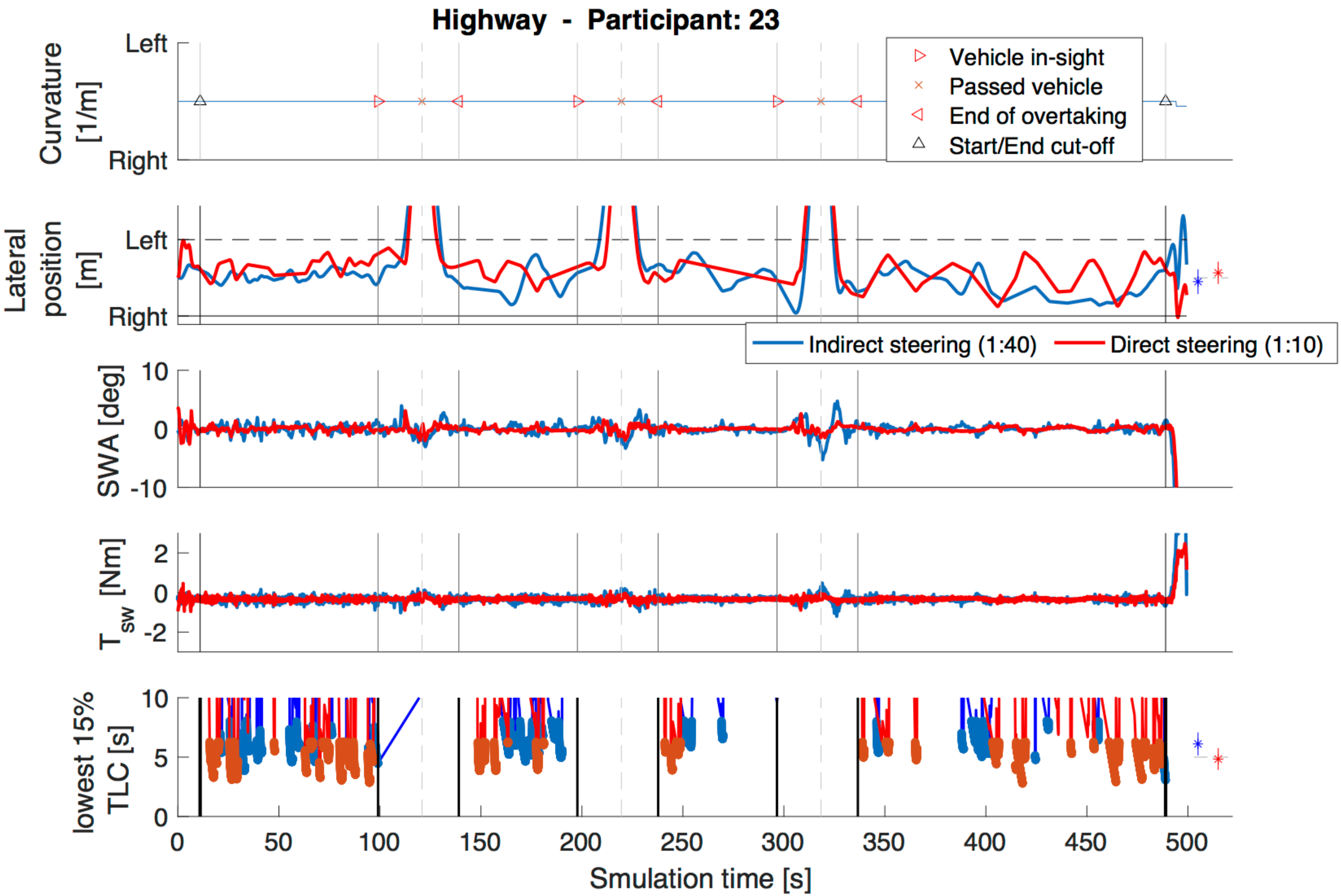

Country road - Participant: 22
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_sw [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



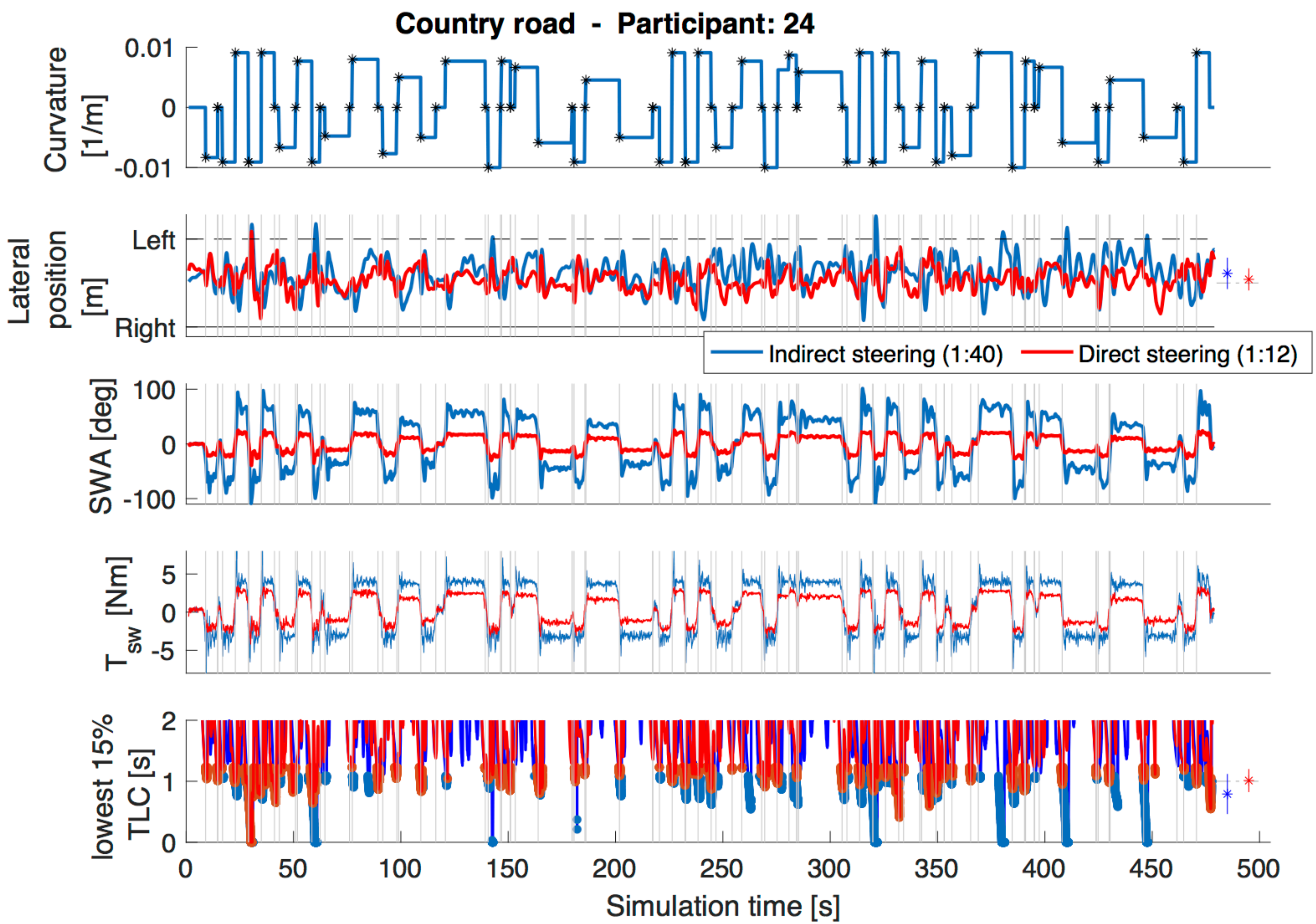
Highway - Participant: 22
Curvature [1/m]
Left
Right
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]

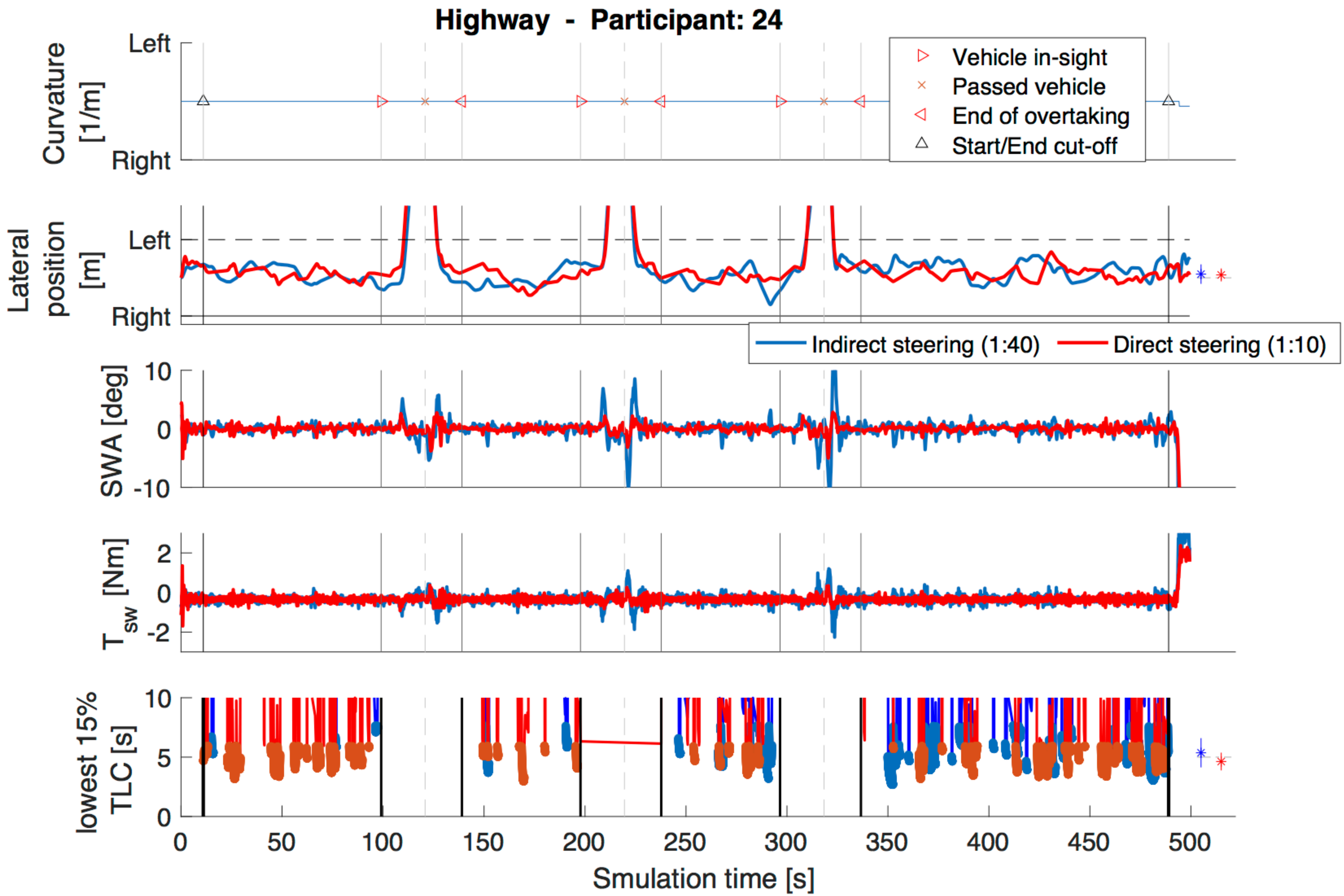


Country road - Participant: 23
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_{sw} [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]



Highway - Participant: 23
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T sw [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]


Country road - Participant: 24
Curvature [1/m]
0.01
0
-0.01
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:12)
SWA [deg]
100
0
-100
T_sw [Nm]
5
0
-5
lowest 15% TLC [s]
2
1
0
0
50
100
150
200
250
300
350
400
450
500
Simulation time [s]


Highway - Participant: 24
Vehicle in-sight
Passed vehicle
End of overtaking
Start/End cut-off
Curvature [1/m]
Left
Right
Lateral position [m]
Left
Right
Indirect steering (1:40)
Direct steering (1:10)
SWA [deg]
10
0
-10
T_{sw} [Nm]
2
0
-2
lowest 15% TLC [s]
10
5
0
0
50
100
150
200
250
300
350
400
450
500
Smulation time [s]