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Do sport modes cause behavioral adaptation?

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ABSTRACT

A key question in transportation research is whether drivers show behavioral adaptation, that is, slower or faster driving, when new technology is introduced into the vehicle. This study investigates behavioral adaptation in response to the sport mode, a technology that alters the vehicle's auditory, throttle-mapping, power-steering, and chassis settings. Based on the literature, it can be hypothesized that the sport mode increases perceived sportiness and encourages faster driving. Oppositely, the sport mode may increase drivers' perceived danger, homeostatically causing them to drive more slowly. These hypotheses were tested using an instrumented vehicle on a test track. Thirty-one drivers were asked to drive as they normally would with different sport mode settings: Baseline, Modified Throttle Mapping (MTM), Artificial Engine Sound enhancement (AESe), MTM and AESe combined (MTM-AESe), and MTM, AESe combined with four-wheel steering, increased damping, and decreased power steering (MTM-AESe-4WS). Post-trial questionnaires showed increased perceived sportiness but no differences in perceived danger for the three MTM conditions compared to Baseline. Furthermore, compared to Baseline, MTM led to higher vehicle accelerations and, with a smaller effect size, a higher time-percentage of driving above the 110 km/h speed limit, but not higher cornering speeds. The AESe condition did not significantly affect perceived sportiness, perceived danger, and driving speed compared to Baseline. These findings suggest that behavioral adaptation is a functional and opportunistic phenomenon rather than mediated by perceived sportiness or perceived danger.

1. Introduction

The ability to adapt to changing circumstances is essential when it comes to driving through traffic. For example, experienced drivers are able to anticipate hazards and decelerate in time where necessary (Underwood et al., 2011; Vlakveld, 2011). However, sometimes drivers adapt in a way that is unexpected, a phenomenon referred to as behavioral adaptation (OECD, 1990). More specifically, behavioral adaptation has been defined as "*those behaviors which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change*" (OECD, 1990, p. 23). Behavioral adaptation may manifest itself as a "*continuum of effects ranging from a positive increase in safety to a decrease in safety*" (p. 23). The term risk compensation

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(Elvik et al., 2009) is often used to describe behavioral adaptation that results in decreased safety, such as faster driving or driving with shorter headways.

Concerns about behavioral adaptation are frequently raised when introducing advanced driver assistance systems (ADAS) (for reviews, see Rudin-Brown & Jamson, 2013; Saad, 2006; Sullivan et al., 2016). Specific examples include adopting shorter headways when driving with a forward collision warning system (Reinmueller et al., 2020) and driving faster when using a lane-keeping assistance system (Melman et al., 2017). In these cases, the intended safety benefits of ADAS are not realized to the fullest extent because drivers take more risks when receiving assistance. It should be emphasized that behavioral adaptation is not necessarily a negative occurrence. Cocron et al. (2011), for example, noted that drivers of electric vehicles are aware of the fact that their vehicles emit little noise and therefore report driving more cautiously in the vicinity of pedestrians and cyclists.

Behavioral adaptation may also occur when the vehicle’s capabilities themselves are changed. In a cross-sectional study, Horswill and Coster (2002) showed positive correlations between observed vehicle speed and physical characteristics of the vehicle, such as engine power. Other examples of behavioral adaptation are vehicles that are driven faster in the snow when fitted with studded tires (Rumar et al., 1976) or shorter gaps that are accepted when vehicles have better acceleration capabilities (Evans & Herman, 1976).

Understanding behavioral adaptation is increasingly relevant now that a growing number of vehicles allow the vehicle’s characteristics to be adjusted through so-called driving modes, such as the sport or eco mode (for examples of this technology, see Audi, 2021; BMW, 2021; Mercedes-Benz, 2021; Porsche, 2021; Renault, 2021; Volvo, 2021). Through the press of a button, driving modes aim to offer a different driving experience through adjustments in auditory, visual, and haptic feedback. In the sport mode, for example, the vehicle settings are altered to create a more sportive experience. This includes adjustments in the powertrain settings such as a sportier throttle mapping (i.e., a more sensitive throttle pedal) and a more aggressive gear-changing strategy (i.e., staying longer in lower gears), but also adjustments that do not affect vehicle handling but aim to change the driver’s perception, such as artificial engine sound enhancement and dashboard lighting.

According to Elvik et al. (2009), the degree of behavioral adaptation depends on whether road users experience a benefit in changing behavior, such as time gain. In the above-mentioned examples of vehicle modifications, this is clearly the case. For example, vehicles fitted with studded tires allow for a higher cornering speed than vehicles with regular tires. Sport modes do not affect the theoretical performance envelope of the vehicle (i.e., maximum engine power and maximum tire grip remain the same) but increase the effective performance envelope (i.e., make it less effortful to accelerate) and intend to create the subjective experience of sportiness. So far, no research in real vehicles seems to exist that has examined its effects on driving behavior. Although it may be expected that drivers exploit the sport mode to accelerate to a cruising speed more quickly, whether the sport mode also causes behavioral adaptation in the form of driving fast through curves or speeding is unknown.

Two alternative mechanisms may explain drivers’ choice of speed when driving in a sport mode. On the one hand, it can be hypothesized that sportier auditory, visual, and haptic feedback encourages drivers to *increase* driving speed because drivers associate a sportier vehicle with a more sportive driving style. In the literature, speeding has been found for sports cars that have a higher maximum engine power (and thus higher maximum speed) compared to vehicles with lower engine power (e.g., Horswill & Coster, 2002; Krahé & Fenske, 2002; Melman et al., 2021b). Similarly, for the sport mode, it can be hypothesized that the increased perceived sportiness causes drivers to drive faster.

On the other hand, sporty vehicle settings can be argued to increase drivers’ perceived danger due to the increased feedback received (e.g., increase in engine sound and vibrations), and hence, cause a *reduction* in driving speed, a mechanism consistent with the risk homeostasis theory (Wilde, 1998). In the same vein, it has been argued that older models of cars are driven at a slower speed than modern cars, speculatively because these cars provide a more dangerous experience, with more noise and vibrations (Fosser & Christensen, 1998). Previous psychoacoustic studies concur that increased engine volume or the presence of engine sound causes drivers to drive slower (Hellier et al., 2011; Horswill & McKenna, 1999) and more accurately estimate their speed (Evans, 1970; Horswill & Plooy, 2008). Note that the risk homeostasis theory has been extensively criticized, primarily because it seems to suggest that any safety-related intervention will fail to have an effect on accident rates, something that is clearly incompatible with the available evidence (Evans, 1986; Vaa, 2007). At the same time, there is much support for the notion that drivers adapt their driving speed to the situation in conjunction with the risk they perceive (e.g., Kolekar et al., 2021; Trimpop, 1996; Wilde, 2013).

As literature provides us with two competing hypotheses, we decided to examine the effect of sport mode settings on drivers’ speed. The present study measured behavioral adaptation operationalized as driving speed in an instrumented vehicle while driving the same test-track route for different combinations of active components used in a commercial sport driving mode. More specifically, we tested five conditions: (1) Baseline (equivalent to Renault’s eco mode), (2) Modified Throttle Mapping (MTM), (3) Artificial Engine Sound enhancement (AESe), (4) MTM and AESe combined (MTM-AESe), and (5) MTM, AESe combined with four-wheel steering, increased variable damping, and decreased power steering assistance (MTM-AESe-4WS). The settings of each system are the same as the one used in Renault’s MultiSense sport mode and were previously described in Melman et al. (2021a). Condition 5 (MTM-AESe-4WS) is identical to Renault’s sport mode (i.e., it incorporates all systems used in sport mode except the cockpit lighting color adjustments and dashboard interface), whereas Condition 4 (MTM-AESe) is the combination of Condition 2 (MTM) and Condition 3 (AESe). In the analysis, we investigated the effects of the systems on longitudinal driving behavior (i.e., speed and acceleration), combined with a location-specific analysis to discover where on the test track differences between the conditions emerged.

Apart from measuring driving speed and other vehicle-state variables, a post-trial questionnaire was used to measure the two constructs underlying our hypotheses: perceived sportiness and perceived danger. Several additional items were included that could help clarify why or how drivers adapt their behavior. More specifically, we queried the extent to which participants noticed relevant vehicle characteristics (see Elvik et al., 2009, who pointed out that the degree of behavioral adaptation depends on the noticeability of the feedback), and we measured the perceived effort in steering and accelerating (see Fuller, 2005; Melman et al., 2018, who noted that perceived effort might govern behavioral adaptation).

The current study is a conceptual replication of a fixed-base simulator study (Melman et al., 2021b) that investigated how perceived sportiness and driving behavior are affected by artificial engine sounds and modified throttle mapping (i.e., a more sensitive throttle pedal). In that study, the enhanced engine sound was simulated via a virtually elevated rpm, whereas the current study amplifies the natural engine sounds through the in-cabin speakers. The modified throttle mapping was similar in both studies. The elevated rpm sound led to increased perceived sportiness as assessed through self-reports, whereas no statistically significant increase or decrease in driving speed was observed, i.e., behavioral adaptation did not occur. The same study also showed that modified throttle mapping only led to higher vehicle accelerations just after driving away from a standstill, while cruising speed was unaffected, which again indicates that behavioral adaptation did not occur. However, whether these results replicate in a production vehicle is still unknown. Human perception is substantially different in a real vehicle than in the driving simulator that was used because the driving simulator produced no vibratory or vestibular feedback, and drivers in simulators do not experience physical risk (De Winter & De Groot, 2012; Melman et al., 2021b).

2. Methods

2.1. Participants

Thirty-one participants (29 males, 1 female, 1 ‘preferred not to say’) between 20 and 59 years old ($M = 44.3$, $SD = 10.6$) volunteered for the test track experiment. The participants were all employees of Renault, Paris, and the majority were engineers and technicians. In response to the question ‘On average, how often did you drive a vehicle in the last 12 months’, 9 participants reported every day, 14 reported 4 to 6 days a week, 7 reported 1–3 days a week, and 1 reported once a month to once a week. Regarding mileage in the past 12 months, 2 reported 1001–5000 km, 5 reported 5001–10000 km, 9 reported 10001–15000 km, 8 reported 15001–20000 km, 2 reported 20001–25000 km, 2 reported 25001–30000 km, and 3 reported 35001–50000 km. To the question ‘How often do you drive on the CTA track?’ (i.e., the test track of Renault), 6 drivers reported never having driven it, 5 reported less than once a month, 10 reported between once a week and once a month, 5 reported once a week, and 5 reported 1–3 times a week. All participants reported having heard of the eco, comfort, and sport modes. Twenty-four participants had driven the sport mode at least once. The research was approved by Renault, and all participants provided written informed consent.

2.2. Experimental vehicle

The instrumented vehicle used in the current study was a Renault Talisman Phase 2 (see Fig. 1-left), engine type R9M, 1.6 L Diesel, with a maximum engine power of 160 kW, a maximum speed of 207 km/h, an automatic transmission, and a 0 to 100 km/h acceleration time of 9.6 s. The vehicle was equipped with the Paris Initiale option, which included four-wheel steering, variable damping, and a Bose sound system comprising 13 speakers and a subwoofer. The experimental conditions and corresponding vehicle settings were switched using a mobile phone connected to a dSPACE MicroAutoBox. The CAN signals were recorded at frequencies between 10 Hz and 100 Hz. The GPS location and acceleration were recorded using a Vbox at 100 Hz (see Fig. 1-right) and calibrated each day. Finally, the same dashboard interface and blue ambient lighting colors were used for all conditions to prevent drivers from being informed about the used condition via visual information.

3. Independent variables and design

All participants drove in all of the following five conditions, where the first condition was identical to Renault’s eco mode, the fifth condition was identical to Renault’s sport mode, and Conditions 2, 3, and 4 represented a combination of eco- and sport-mode features.

Fig. 1. The experimental vehicle, a Talisman phase 2 (left), with the VBOX GPS antenna (right).

1. Baseline
2. Modified throttle mapping (MTM)
3. Artificial engine sound enhancement (AESe)
4. Modified throttle mapping and artificial engine sound enhancement combined (MTM-AESe)
5. Modified throttle mapping, artificial engine sound enhancement, four-wheel steering, increased variable damping, and decreased power steering combined (MTM-AESe-4WS).

The MTM condition involved an altered throttle mapping, where a given driver's throttle depression ('throttle driver') resulted in a higher normalized requested engine torque ('throttle engine') (see Fig. 2-left). Additionally, MTM increased the gear shift point in the rpm range (i.e., allowing a higher rpm before changing gears). For example, for a 'throttle driver' of 40%, the gear changed from 3rd to 4th at 35 km/h for Baseline, whereas for MTM, this was 43 km/h. The effect of this gear-changing strategy on the gear distribution for this experiment is shown in Fig. 2-right. Finally, for the MTM condition, engine braking was done at higher engine speeds. The maximum engine power (160 kW) was the same for all conditions.

The AESe condition artificially amplified the natural engine sounds through the in-cabin speakers. More specifically, compared to Baseline, AESe increased the engine's second harmonic by 3 dB for engine speeds below 2000 rpm, by 7 dB for engine speeds between 2000 and 3500 rpm, and no enhancement was provided above 3500 rpm. The AESe setting was identical to the AESe setting used in Renault's sport mode. Subjectively, this resulted in a roaring engine sound.

The MTM-AESe-4WS condition added four-wheel steering, increased vertical damping, and decreased power steering to the MTM and AESe conditions. The four-wheel steering system applied countersteering, where the rear wheels were turned in the opposite direction from the front wheels to increase the vehicle's yaw response (i.e., a smaller steering wheel angle was required to drive through a curve). These effects are visualized in Fig. 3 (see also Melman et al., 2021a, for more detailed information). The suspension damping coefficient increased about 3.5 times for MTM-AESe-4WS compared to Baseline (Melman et al., 2021a). The power steering assistance decreased, resulting in higher driver steering torques (see Fig. 3).

It is noted that while 4WS involves dedicated hardware, MTM and AESe are software-based, i.e., these features aim to increase the perceived sportiness of the vehicle without requiring potentially costly hardware (Melman et al., 2021b). It is further noted that all five conditions offered the same dynamic envelope of the vehicle, i.e., if the throttle were fully depressed, the acceleration and gear-changing moments of the car would be identical. However, the presumed mechanisms of MTM and AESe on behavioral adaptation are quite different: MTM offers higher instantaneous acceleration capabilities than Baseline since, with MTM, the vehicle generally drives in a lower gear. Consequently, the driver can acquire a target speed more easily, without pressing the throttle deeply. In comparison, the AESe condition changes nothing to the responsiveness of the vehicle; any change in driving speed would be due to the illusion of driving a sportier vehicle (Melman et al., 2021b).

The participants each drove the five conditions in counterbalanced order. Because a complete permutation of the five conditions would require a very high number of participants ($5 \times 4 \times 3 \times 2 \times 1 = 120$), a more economical counterbalancing method was used, as defined by Williams (1949). For five conditions, Williams proposes a counterbalancing approach involving ten different orders. This was repeated three times for the first 30 participants in our experiment, with one additional order for the last participant.

3.1. Road environment

The experiment was performed on Renault's test circuit in Aubevoye, France. The participants drove on a 10.4-km route. The route consisted of a stop-and-go section (0.6 km; Fig. 4), where drivers had to stop the vehicle and drive away from a standstill. The stop-and-

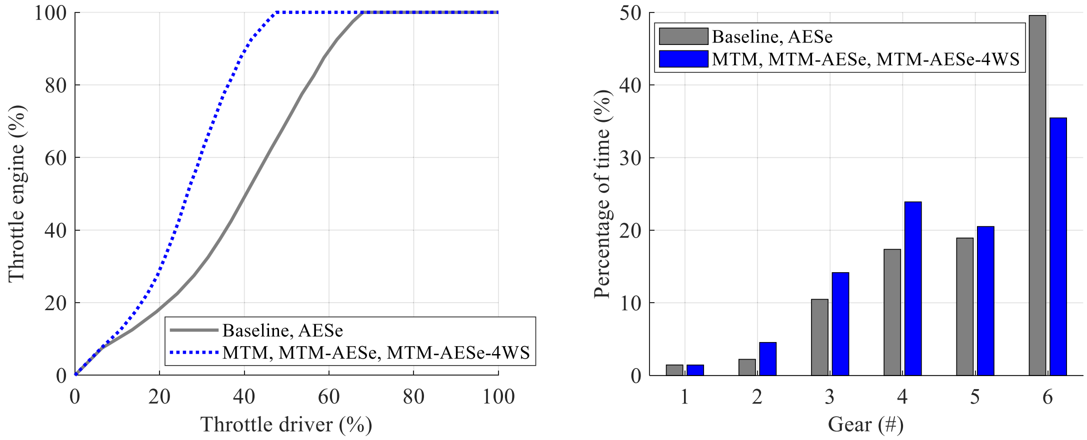

Fig. 2. The modified throttle mapping (left) and the gear distribution during the driven route for all participants (right). Both graphs were created using the data recordings of the experiment.

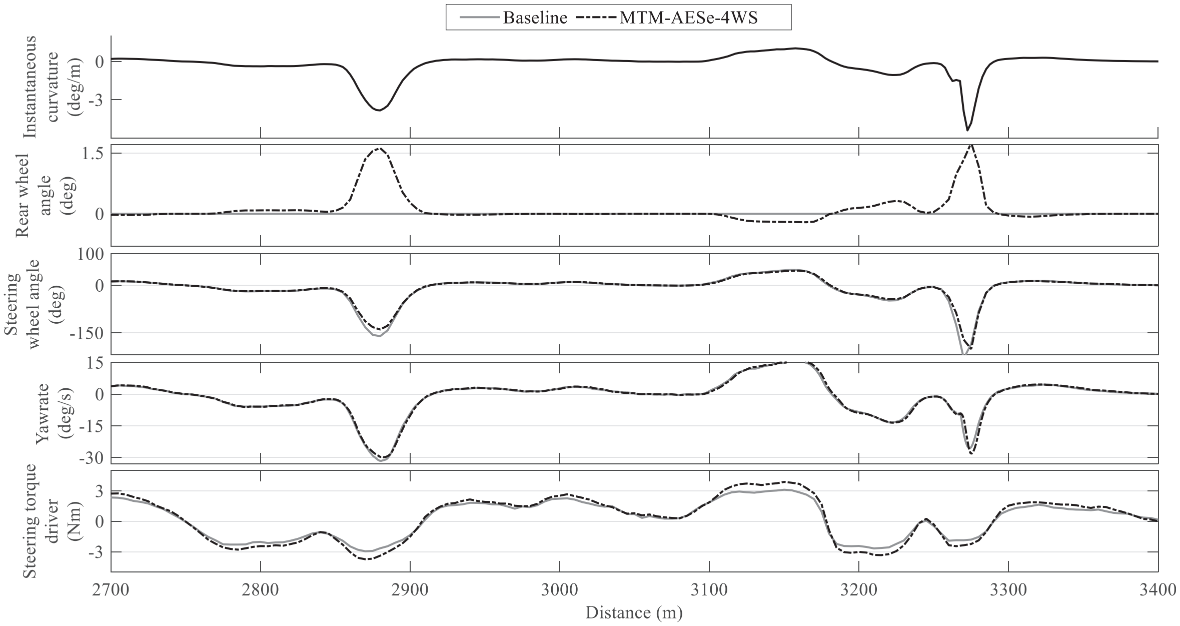

Fig. 3. Illustration of four-wheel steering and power steering adjustments in the MTM-AESe-RWS condition versus the Baseline condition. The instantaneous curvature is calculated as the yaw rate/speed. The figure depicts two sharp curves (2880 m and 3270 m). The figure is made using the data recordings and shows the mean behavior averaged over all 31 participants.

go section was analyzed separately, resulting in a 9.8 km total route for the general analysis. The route consisted of a one-way two-lane road with a speed limit of 110 km/h and 90 km/h, except for the connection between two test tracks that consisted of a two-way single-lane road with a speed limit of 50 km/h (see Fig. 4). Before entering the northern part of the test track, drivers had to stop in front of a stop sign and turn right. Very little traffic was encountered during the experiment; out of the 155 trials (5 conditions × 31 participants), only five trials encountered one or more vehicles. The experiment was conducted in dry weather for all drivers (the experiment was conducted in June 2021).

3.2. Procedure

The study was advertised, without stating the aim, in the general Renault newsletter that was sent to all employees. The participants read and signed a consent form and completed a questionnaire on their demographics, driving experience, and familiarity with the test track. The instruction sheet mentioned that the purpose of the study was to investigate their driving behavior and feelings while driving with different driving-experience enhancement systems. It also mentioned that the experiment consisted of five trials

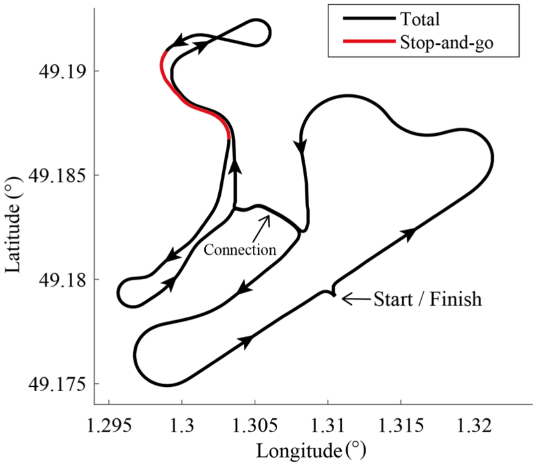

Fig. 4. The experimental route on the Renault test track in Aubevoye, France. The driving direction is indicated by arrows, and the connection is driven in both directions.

driven on the test track and that in each trial, they would be supported by a different set of driving-experience enhancement systems. Participants were asked to drive as they usually do on the test track and adhere to the traffic rules indicated by road signs next to the road.

The first trial of the experiment was a familiarization run to let the driver become familiar with the route and the Baseline conditions. The participants were told that this trial would not be analyzed. During the first trial only, the experimenter, who was sitting next to the driver, gave navigation instructions, and the stop-and-go was practiced. After the familiarization trial, the car was parked, and the experiment started.

In each experimental trial, participants drove in one of the five conditions (Baseline, MTM, AESe, MTM-AESe, or MTM-AESe-4WS). The participants were not informed about the settings of the conditions in this blinded experiment, and the dashboard did not give an indication of the vehicle settings that were currently active. After each trial, participants stepped out of the vehicle and completed a paper-and-pencil questionnaire about their driving experience. During the entire experiment, the experimenter was sitting next to the driver without talking. The entire experiment took approximately 75 min per participant. The consent form and the personal details questionnaire were written in French, and the post-trial questionnaire was written in English to replicate Melman et al. (2021b).

3.3. Dependent measures

The dependent measures were categorized into self-reported experience and driving behavior, similar to the simulator study by Melman et al. (2021b). The driving behavior measures were calculated for the route, excluding the stop-and-go section (9.8 km). Furthermore, for all measures (except the stop-and-go section), speeds below 10 km/h were excluded from the data to remove the influence of the stop sign on the measures.

Self-Reported Experience. After each trial, participants completed a questionnaire containing 14 items on a five-point scale.

The first four items investigated drivers' perceived effort for Q1 accelerating, Q2 steering, Q3 braking, and Q4 maintaining speed, from low to high. This was followed by four items that investigated whether the drivers perceived the vehicle settings: Q5 throttle responsiveness (low to high), Q6 brake responsiveness (low to high), Q7 engine sound (quiet to loud), and Q8 steering responsiveness (low to high). Finally, seven items polled whether participants had experienced the vehicle as Q9 not sporty/sporty, Q10 not likable/likable, Q11 not comfortable/comfortable, Q12 safe/dangerous, Q13 not agile/agile, and Q14 raising awareness/sleep-inducing. The two main items were Q9 (perceived sportiness) and Q12 (perceived danger).

Driving Behavior. The following driving behavioral measures were calculated over the total track, excluding the stop-and-go section: The speed measures below are the main measures of interest.

- Mean speed (km/h). Mean speed is often used as an index of road safety: an increase in speed reduces the available time to respond in an emergency scenario and increases the probability of being involved in a crash (Aarts & Van Schagen, 2006; Pei et al., 2012).
- Max speed (km/h). The maximum speed that was recorded.
- Mean cornering speed (km/h). This measure shows the speeds driven during the cornering sections for instantaneous curvatures (calculated by the yaw rate/speed) >0.7 deg/m. Using this threshold, 16% of the route was categorized as 'curve'.
- Percentage above 110 km/h (%). The percentage of time above the 110 km/h speed limit was calculated as a percentage of the total time driven in the 110 km/h speed limit section.

In addition, we calculated nine longitudinal driver behavior measures that provide more insight into how drivers drove with the different combinations of sport mode components.

- Mean absolute longitudinal acceleration (m/s^2). A high mean absolute longitudinal acceleration can be seen as sporty driving (Ericsson, 2001; Martinez et al., 2018).
- Mean throttle driver (%). A measure of how deeply drivers pressed the accelerator on average. A lower value is expected for the three MTM conditions compared to AES and Baseline, as less 'throttle driver' is needed to drive with a certain speed (see also the simulator study by Melman et al., 2021b).
- Max brake pressure (bar). This measure indicates how hard the driver braked. Hard braking is an indication of sportive driving or approaching a curve at high speed.
- Throttle driver release time (%). In the literature, this measure is also referred to as coasting and has been interpreted as indicative of uncertainty or a delay in decision-making (Houtenbos et al., 2017; Yeo et al., 2010). It is also a corollary of having accelerated too much, resulting in an overshoot of speed and a subsequent throttle release. This measure was previously found to be strongly affected by modifications in throttle mapping (Melman et al., 2021b).
- Fuel consumption per km (cm^3/km). An additional measure to quantify the impact of different sport mode components on fuel consumption. Higher fuel consumption is expected when driving with the MTM conditions compared to Baseline due to the altered gear-changing strategy (i.e., driving in a lower gear).
- Mean gear. A measure that captures the average used gear and is expected to be lower for the MTM than Baseline due to the more sportive gear changing strategy.

For the stop-and-go section, the following measure was calculated:

- Mean acceleration during the first five seconds (m/s^2). This measure indicates sporty driving. The start of each trial was determined based on the moment the throttle position exceeded 0%. A previous simulator study showed higher accelerations when driving with MTM compared to Baseline (Melman et al., 2021b).

3.4. *Statistical analyses*

For each measure and each of the five experimental conditions, the mean and standard deviation (*SD*) across the 31 participants was computed. Pairwise comparisons between conditions were performed using paired-samples *t*-tests. Because of the large number of statistical comparisons made, a conservative alpha value of 0.005 was adopted (Benjamin et al., 2018). A reviewer noted that a conservative alpha value might cause Type II errors and may therefore give the unfair impression that no behavioral adaptation exists. Therefore, we also report results for a more liberal alpha value of 0.05. We caution the reader that a number of the observed statistically significant effects could be false positives. Finally, within-subject effect sizes d_z were calculated according to Faul et al. (2007).

4. Results

4.1. *Self-reported experience*

Fig. 5 shows the means and 95% confidence intervals for the 14 self-report items described in the section ‘dependent measures’. Compared to Baseline, MTM, MTM-AESe, and MTM-AESe-4WS resulted in significantly ($p < 0.005$) higher reported engine responsiveness (Q5) and reduced acceleration effort (Q1), while AESe, MTM-AESe, and MTM-AESe-4WS resulted in higher perceived engine sound (Q7). Furthermore, four-wheel steering (MTM-AESe-4WS) resulted in significantly (p < 0.005) higher perceived steering effort (Q2) but not a significant difference ($p > 0.05$) in steering responsiveness (Q8) and agility (Q13) compared to Baseline.

The perceived sportiness (Q9) was significantly ($p < 0.005$) higher for MTM ($M = 3.32$), MTM-AESe ($M = 3.58$), and MTM-AESe-4WS ($M = 3.97$) compared to Baseline ($M = 2.32$). Perceived danger (Q12) showed no significant differences ($p > 0.05$) from Baseline ($M = 2.48$) for MTM ($M = 2.32$), AESe ($M = 2.42$), MTM-AESe ($M = 2.45$), and MTM-AESe-4WS ($M = 2.16$). Additionally, it was found that likeability (Q10) was higher for MTM ($p < 0.005$) and MTM-AESe-4WS ($p < 0.05$) compared to Baseline. The MTM conditions (MTM, MTM-AESe, and MTM-AESe-4WS) resulted in significantly ($p < 0.005$) lower ‘sleep inducing’ ratings (Q14) than Baseline. No significant differences were found for the comfort (Q11) and speed control effort (Q4) ratings. Finally, it was interesting that the MTM, AESe, and MTM-AESe-4WS conditions increased perceived brake responsiveness (Q6), even though the brake pedal itself was not modified.

4.2. *Driving behavior*

Table 1 shows the means, standard deviations, and results of the pairwise comparisons. The mean speed, maximum speed, and speed limit violation time for the three MTM conditions (MTM, MTM-AESe, MTM-AESe-4WS) were higher compared to Baseline, although often not statistically significant ($p > 0.05$). The mean cornering speed was equivalent for the five conditions and did not differ significantly ($p > 0.05$) from the Baseline condition.

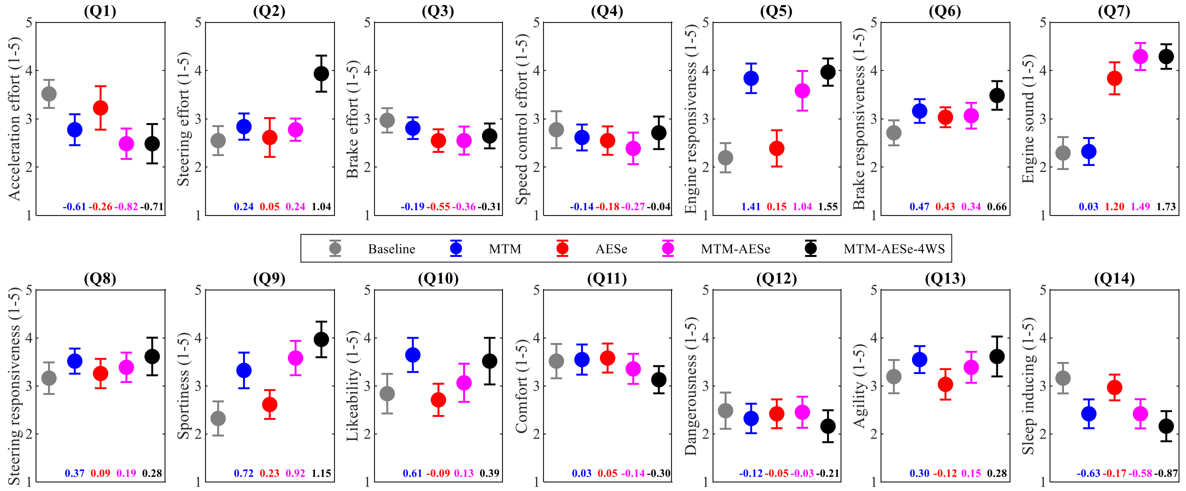

Fig. 5. The questionnaire results per item and experimental condition. The figure depicts the means (circles) and within-subject 95% confidence intervals calculated according to Morey (2008). Q1–Q4 concern perceived effort, Q5–Q8 concern perceived driving mode features, and Q9–Q14 concern other aspects of subjective experience. The bottom of each figure shows the Cohen’s d_z for MTM, AESe, MTM-AESe, and MTM-AESe-4WS compared to Baseline ($|d_z| > 0.367$: $p < 0.05$, $|d_z| > 0.545$: $p < 0.005$).

Table 1
Means, standard deviation (in parentheses), and pairwise comparisons for each driving behavior measure.

	Conditions					Pairwise comparisons			
	Baseline **1**	MTM **2**	AESe **3**	MTM-AESe **4**	MTM-AESe-4WS **5**	**1–2**	**1–3**	**1–4**	**1–5**
Mean speed (km/h)	79.40 (5.63)	80.15 (5.40)	78.79 (5.45)	79.73 (5.88)	80.85 (5.85)	0.24	−0.23	0.08	*0.51*
Maximum speed (km/h)	115.01 (8.04)	116.92 (7.60)	114.03 (8.45)	116.12 (8.48)	116.84 (7.83)	0.35	−0.16	0.21	0.31
Mean cornering speed (km/h)	48.45 (3.55)	48.40 (3.31)	48.08 (3.73)	48.09 (3.71)	48.60 (3.93)	−0.03	−0.25	−0.15	0.09
Percentage above 110 km/h (%)	5.93 (9.45)	7.55 (9.36)	5.54 (9.04)	6.98 (9.51)	8.50 (12.02)	*0.38*	−0.12	0.27	*0.51*
Mean abs long acc (m/s^2)	0.727 (0.103)	0.772 (0.120)	0.727 (0.111)	0.773 (0.113)	0.783 (0.104)	**0.72**	0.01	**0.61**	**0.96**
Mean throttle driver (%)	27.88 (3.34)	18.59 (2.86)	28.02 (3.42)	18.60 (2.88)	19.12 (3.29)	**−4.97**	0.10	**−4.08**	**−4.96**
Max brake pressure (bar)	24.21 (4.75)	23.03 (3.95)	23.68 (4.73)	24.25 (4.98)	24.34 (3.45)	−0.35	−0.16	0.01	0.04
Throttle driver release time (%)	35.50 (5.66)	37.35 (6.44)	35.22 (6.38)	37.44 (6.22)	36.74 (5.92)	**0.65**	−0.10	**0.63**	**0.62**
Fuel consumption (cm^3/km)	84.55 (11.00)	88.98 (12.14)	86.75 (13.53)	90.41 (13.08)	90.94 (10.45)	**0.59**	0.24	**0.59**	**0.82**
Mean gear (-)	5.10 (0.13)	4.76 (0.21)	5.07 (0.17)	4.74 (0.21)	4.77 (0.15)	**−3.04**	*−0.49*	**−3.27**	**−4.57**
Stop-and-go section									
Mean acceleration during the first five seconds (m/s^2)	1.92 (0.45)	2.20 (0.44)	1.91 (0.46)	2.28 (0.37)	2.28 (0.44)	**0.74**	−0.01	**1.11**	**1.13**

Note. $|d_z| > 0.367$: $p < 0.05$ (marked in italics), $|d_z| > 0.545$ (marked in boldface): $p < 0.005$.

On an absolute scale, the speed differences between conditions were rather small. Indicatively, participants' mean speed, maximum speed, mean cornering speed, and driving time above the speed limit were 0.75 km/h higher, 1.91 km/h higher, 0.05 km/h lower, and 1.63% higher in MTM compared to Baseline (see Table 1). For MTM-AESe-4WS compared to Baseline, the values for these four respective measures were 1.45 km/h, 1.84 km/h, 0.15 km/h, and 2.57% higher (see Table 1).

The lowest speed was found for AESe, but not significantly different from Baseline on any of the four speed-related measures. However, the mean gear was significantly ($p < 0.05$) lower for AESe compared to Baseline, suggesting that AESe evoked a cautious driving style. Table 1 further shows that participants adopted a more sporty driving style with MTM (MTM, MTM-AESe, and MTM-AESe-4WS) than Baseline, with higher mean absolute accelerations and more throttle fluctuations (higher throttle-release time).

Fig. 6 shows the mean speed, throttle, and braking as a function of traveled distance. Furthermore, Fig. 6 shows the speed difference for the three MTM conditions averaged (i.e., the average of MTM, MTM-AESe, and MTM-AESe-4WS) relative to Baseline and AESe averaged. Compared to Baseline/AESe, the largest speed differences (up to 5.5 km/h) were found when accelerating out of curves, after the stop sign, and after the stop-and-go section. In other words, the results indicate that it is during the acceleration phases that the difference between the MTM conditions and Baseline/AESe was largest.

Fig. 7 shows the participants' mean acceleration during the first 5 s after driving away from the stop-and-go section per condition. This figure confirms that drivers adopted higher accelerations when driving with MTM, MTM-AESe, and MTM-AESe-4WS than with Baseline and AESe. After about 5 s, the accelerations were equivalent for all five conditions, in line with the simulator study by Melman et al. (2021b).

Finally, the fuel consumption was higher for MTM-AESe and MTM-AESe-4WS compared to Baseline. This is possibly the result of the gear-change strategy, where the vehicle stayed longer in lower gears (see Table 1).

5. Discussion

Two competing hypotheses regarding the effect of sport mode settings on behavioral adaptation were considered in this research: a speed increase due to increased perceived sportiness (cf. Horswill & Coster, 2002) and a speed reduction due to increased perceived danger (cf. Wilde, 1998). We tested these two hypotheses by means of a test-track experiment using an instrumented vehicle for different combinations of sport mode components. More specifically, we investigated five conditions: Baseline, Modified Throttle Mapping (MTM), Artificial Engine Sound enhancement (AESe), MTM and AESe combined (MTM-AESe), and MTM, AESe combined with four-wheel steering, increased damping, and decreased power steering (MTM-AESe-4WS).

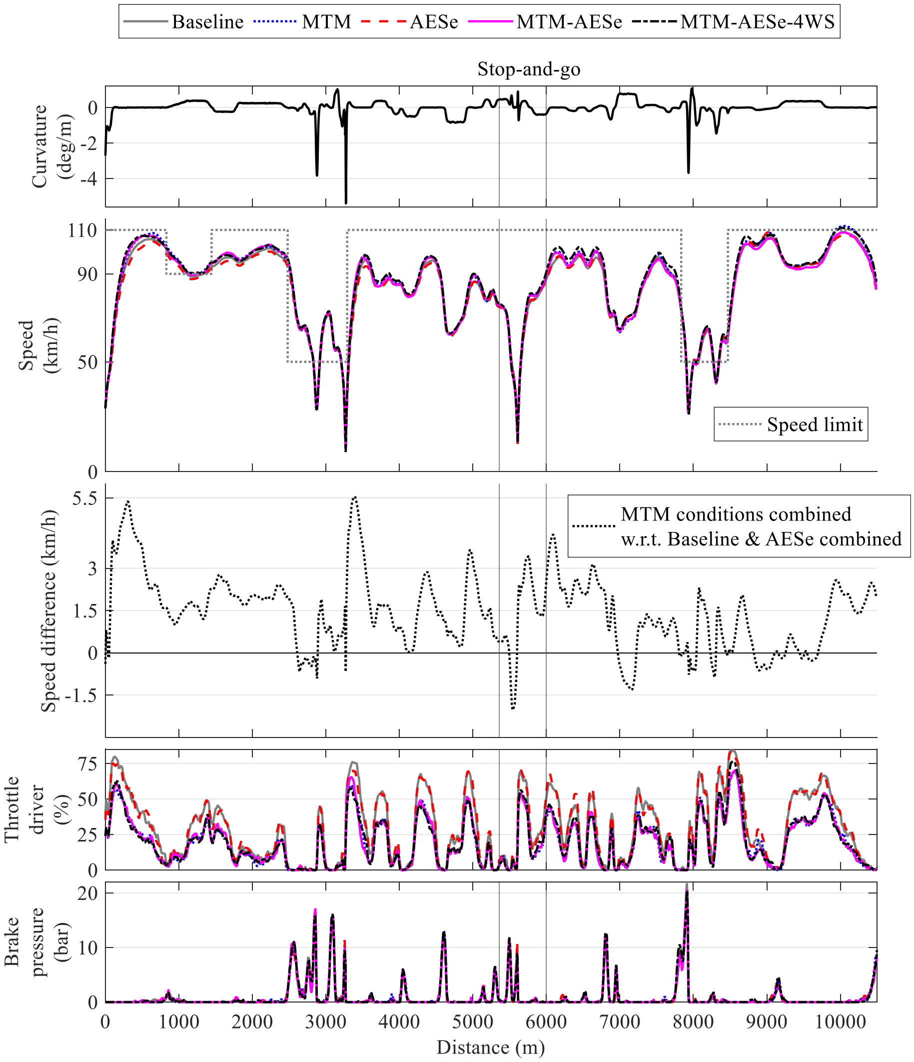

Fig. 6. The mean driving behavior per condition averaged over all 31 participants. (1) instantaneous curvature (yaw rate/speed), (2) driving speed, (3) driving speed of the three MTM conditions averaged relative to Baseline, AESe averaged (positive values mean that participants drove faster with MTM compared to without), (4) throttle driver, and (5) brake pressure. Note that the vehicle speed does not drop to exactly 0 km/h during the stop-and-go and the stop sign (at 3300 m); this is because participants stopped their vehicles at slightly different positions on the road.

The results suggest that the drivers, in the aggregate, noticed each sport mode setting. That is, compared to Baseline, participants reported increased engine responsiveness for MTM (Q5), a higher engine sound volume for AESe (Q7), and an increased effort required to steer (Q2) for the MTM-AESe-4WS condition. These findings suggest that necessary preconditions for behavioral adaptation were present.

The sport mode was hypothesized to increase perceived sportiness and thus encourage faster driving. The hypothesis of faster driving was not supported for the AESe condition; in fact, perceived sportiness was unaffected, and there were some tendencies for slower driving with AESe compared to Baseline. However, the hypothesis received mixed support for the MTM feature: compared to Baseline, the three MTM conditions yielded increased perceived sportiness ratings and caused increased speeds while accelerating out of curves (Fig. 6) or while accelerating from a standstill (Fig. 7). The MTM condition also caused, albeit with a small effect size, an elevated percentage of time driving above the 110 km/h speed limit. However, the MTM conditions did not cause statistically significant differences in cornering speed compared to Baseline. Thus, MTM appeared to cause increased accelerations but not faster cornering. Note that the higher mean speed of the MTM conditions compared to Baseline can directly be explained by the increased accelerations (in fact, achieving a higher mean acceleration while maintaining the same average speed is only possible if adopting a lower speed on the remaining part of the track). In conclusion, the findings suggest that behavioral adaptation was functional and opportunistic (i.e., increased acceleration to target speeds because of the given opportunity to accelerate more easily) rather than

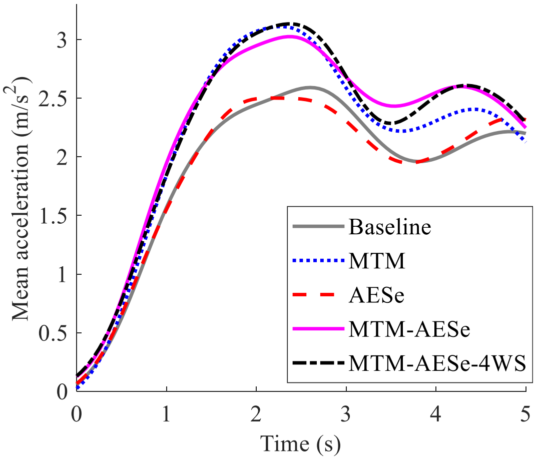

Fig. 7. Mean vehicle acceleration after driving away from the stop-and-go section per condition, averaged over all participants during the first 5 s at the start and stop location.

instigated by drivers feeling ‘sporty’ and hence adopting a riskier driving style. The current findings correspond to the examples cited in the introduction, where behavioral adaptation was said to be more likely when the technology offers a benefit to the driver.

The presumed cause of the increased acceleration is that, for a given throttle depression in the 10–60% range, the MTM conditions yielded higher instantaneous engine power compared to the Baseline condition (see Fig. 2-left). In addition to the more sensitive pedal (and in contrast to the driving simulator study by Melman et al. (2021b), which simulated an electric engine without gears), more instantaneous engine power was available because the MTM conditions were driven in a lower gear (see Fig. 2-right). Consequently, if the driver presses the pedal to a certain level, acceleration will be higher for MTM compared to Baseline. The driver, in turn, adapts to the sensitive pedal by pressing it less deeply (see ‘throttle driver’ in Fig. 6 and see Melman et al., 2021b, for further explanation in the context of open-loop vs closed-loop driver control). The present acceleration results replicate findings from an earlier simulator-based study by Melman et al. (2021b). However, in this driving simulator experiment, no effect of MTM was found on perceived sportiness, which the authors attributed to the lack of vestibular feedback and large inter-driver variability in a driving simulator.

The competing hypothesis was that the sport modes would cause an increase in perceived danger, in turn causing drivers to compensate by adopting a lower speed compared to the Baseline condition. This hypothesis is rejected since the MTM feature did not cause a reduction but rather a small increase in driving speeds, as discussed above. In addition, the sport modes did not cause an increase in perceived danger. In fact, perceived danger was even slightly lower for the MTM-AESe-4WS condition than for the Baseline condition (2.16 vs 2.48 on the 5-point scale).

A limitation of the current study was that it was conducted with predominantly experienced male drivers. They were familiar with the test track and may have driven faster than the average driver would. Another validity threat is that the daily work of most participants consisted of studying vehicle chassis behavior, as a result of which they may express socially desirable opinions about products of their own company. However, as we noticed in another study in which employees participated in a truck driving study in which they evaluated human-machine interface (HMI) concepts (Bazilinskyy et al., 2019), the opposite may be the case. Our impression was that participants in the current experiment were open-minded, critical, and consciously tried to observe the differences between the vehicle conditions. Future studies should investigate how these results translate to different groups of drivers.

In the current study, there were speed limit signs next to the road, which may have produced a ceiling effect on driving speeds, although participants still drove faster than the 110 km/h speed limit for 5.5 to 8.5% of the time (see Table 1). Future research could replicate our findings on different types of roads and for different types of speed limits. In addition, it would be useful to repeat the current study as part of a field operational test, in which drivers may participate for a period of months and may tend to forget they are participating in an experiment. This would also allow for exploring other aspects of behavioral adaptation, such as the interaction with other road users. Finally, it should be noted that although the MTM condition was well-liked (Q10) relative to the Baseline condition, it caused an increase in fuel consumption of about 6%. In other words, the increased capabilities and likeability ratings come at the price of increased cost. The relatively low likeability score for the Baseline condition is consistent with a driving-simulator experiment by Allison et al. (2022), which found that asking drivers to engage in eco-driving behaviors had a negative impact on drivers’ overall mood. It can therefore be expected that eco modes will be underutilized in real traffic.

6. Conclusions

The current study investigated behavioral adaptation in response to the sport driving mode. Two alternative hypotheses were tested: (1) increased speed due to increased perceived sportiness and (2) decreased speed due to increased perceived danger. The following conclusions are drawn:

- The sport mode setting that makes it easier for drivers to accelerate (i.e., modified throttle mapping) increases perceived sportiness, is well-liked, and causes increased speeds while accelerating out of curves or from a standstill. However, the MTM conditions did not cause detectable differences in mean cornering speed compared to Baseline. Thus, MTM seemed to cause increased accelerations but not riskier driving.
- The sport mode setting that alters the drivers' auditory experience (i.e., artificial engine sound enhancement) is perceived clearly but does not significantly affect perceived sportiness or perceived danger and does not cause drivers to drive faster.

These findings suggest that behavioral adaptation is a functional and opportunistic phenomenon (i.e., increased acceleration to target speeds because of the given opportunity to accelerate more easily) rather than mediated by drivers having the feeling of sportiness or dangerousness.

Apart from the theoretical contribution mentioned above, the present findings may have practical utility for vehicle manufacturers. This study replicates previous simulator-based research (Melman et al., 2021b) in that relatively simple software-based modifications to the vehicle, such as modified throttle mapping, can have a substantial impact on driver perception (e.g., perceived sportiness), and stimulate drivers to reach their target speed more quickly.

CRediT authorship contribution statement

Timo Melman: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **Adriana Tapus:** Conceptualization, Supervision. **Maxime Jublot:** Software, Investigation, Resources. **Xavier Mouton:** Supervision, Funding acquisition, Investigation, Resources. **David Abbink:** Supervision, Conceptualization, Funding acquisition, Project administration. **Joost de Winter:** Supervision, Conceptualization, Methodology, Formal analysis, Validation, Writing – original draft, Writing – review & editing.

Supplementary Material

The values behind the means, standard deviations, and statistical tests are available at https://doi.org/10.4121/20348148.

Declaration of Competing Interest

Timo Melman, Maxime Jublot, and Xavier Mouton are employed by Renault Inc. Timo Melman does his PhD research in collaboration with the Delft University of Technology and ENSTA Paris.

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