Transportation Research Part F 35 (2015) 170–184

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Quantifying drivers' comfort-zone and dread-zone boundaries in left turn across path/opposite direction (LTAP/OD) scenarios

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ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form 24 September 2015
Accepted 7 October 2015
Available online 11 November 2015

Keywords:
Safety margins
Comfort zone
Intersection safety
Left turn
ADAS
Active safety

ABSTRACT

The aim of this study is to quantify drivers' comfort- and dread-zone boundaries in left-turn-across-path/opposite-direction (LTAP/OD) scenarios. These scenarios account for a large fraction of traffic fatalities world-wide. The comfort zone is a dynamic spatiotemporal envelope surrounding the vehicle, within which drivers feel comfortable and safe. The dread zone, a novel concept, describes a zone with a smaller safety margin that drivers will not voluntarily enter, but can push themselves into when conditions provide additional motivation (e.g., when hurried). Quantifying comfort- and dread-zone boundaries in the context of turning left before or after an oncoming vehicle has the potential to inform and improve both the design and driver acceptance of advanced driver assistance systems (ADAS) and autonomous vehicles.

Using a within-subject design, a test-track experiment was conducted with drivers turning an instrumented vehicle left across the path of an oncoming vehicle. The oncoming vehicle was a self-propelled full-sized computer-controlled balloon vehicle going straight at a constant speed (50 km/h). The driver assumed full control of the instrumented vehicle approximately 20 m before the intersection and had to make the decision to turn left before or after the oncoming balloon vehicle. There were two experimental conditions, comfortable driving and hurried driving. Measures for each turn included post-encroachment time (PET), lateral acceleration, and self-reports of comfort and risk. Drivers consistently accepted shorter time gaps and higher lateral accelerations when hurried. We interpret these findings to suggest that drivers invoke two dynamic, contextually-defined safety margins. The first is the comfort-zone boundary, a limit which drivers do not voluntarily cross without *extra motives*. The second is the dread-zone boundary, a more distant limit which drivers do not voluntarily cross even with extra motives. Grouping the responses (high/low) to the driver behavior questionnaire (DBQ) improved the ability to predict the dread-zone boundary PET given the comfort-zone boundary PET.

1. Introduction

1.1. Background

In 2010, traffic crashes were the ninth leading cause of death world-wide and the leading cause of death for men between 15 and 29 (WHO, 2013). Crashes in intersections accounted for 40% of automotive fatalities in the US in 2007 (USDOT, 2009).

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http://dx.doi.org/10.1016/j.trf.2015.10.003
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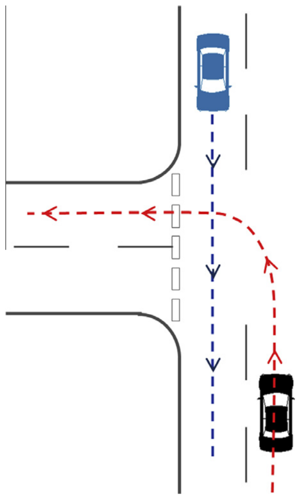

Fig. 1. Vehicle trajectories in the left-turn-across-path/opposite-direction (LTAP/OD) scenario. The blue (gray) vehicle has the right-of-way. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In left-turn-across-path/opposite-direction (LTAP/OD) scenarios (Fig. 1), drivers who want to turn left must decide whether to turn before the approaching vehicle with the right-of-way (Go), or to wait and pass after it (No-Go). Technology that supports the decision not to turn into crossing traffic when there is an imminent risk of a crash has the potential to reduce traffic fatalities significantly.

1.2. The comfort-zone boundary and safety margins in driving

In 1938, Gibson and Crooks presented the theory of field of safe travel. They proposed that drivers dynamically adopt margins between their own vehicle and other road users and the infrastructure in order to feel safe and comfortable. These margins are not absolute; they are constantly influenced by a variety of factors from drivers' character (e.g., risk-taking propensity) to context (e.g., traffic, road conditions). Näätänen and Summala (1974) built upon the ideas proposed by Gibson and Crooks (1938) and introduced the concept of the *comfort zone*. Based on this work we define the comfort zone as an implicit spatiotemporal envelope that extends in front of the driver–vehicle system, within which the driver feels comfortable in everyday normal driving (Fig. 2). The limit of comfortable driving is marked by the *comfort-zone boundary*, which, in the absence of *extra motives*, drivers are unwilling to cross; they feel discomfort when they do cross it. Summala (2007) suggests that drivers may target specific levels of arousal (feelings) as part of the implicit process of adopting a comfort-zone boundary. These feelings may include a balance between conflicting goals, e.g., sensation-seeking or pleasure versus safety or anxiety.

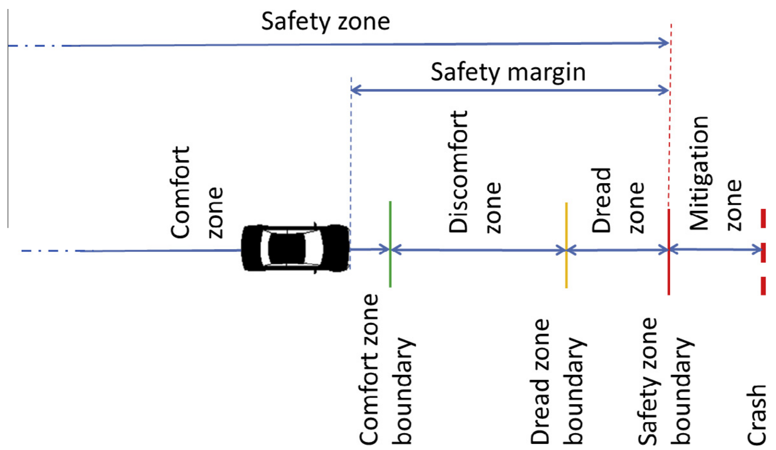

Fig. 2. Zones and boundaries discussed in this paper.

From time to time, drivers cross the comfort-zone boundary voluntarily, due to the dynamics of the situation. When they do, they seek to return to the comfort zone as quickly as they safely can (Gibson & Crooks, 1938; Summala, 2007; Vaa, 2007). Näätänen and Summala (1974) introduced the concept of extra motives to explain why drivers voluntarily accept smaller safety margins in some situations; the term subsumes any and all internal or external forces that motivate the driver to accept levels of discomfort that would normally be unacceptable. Examples include being in a hurry, being angry, and being scared.

When drivers are sufficiently motivated to push themselves past the comfort-zone boundary, they enter what we call the *discomfort zone*. The higher the motivation, the further drivers can push into the discomfort zone. However, there is an implicit spatiotemporal limit beyond which drivers will never go voluntarily, which we define as the *dread-zone boundary*. The comfort-zone boundary is between the comfort zone and the discomfort zone, while the dread-zone boundary is beyond the discomfort zone, between the discomfort zone and the *dread zone*.

The dread zone is the spatiotemporal region between the dread-zone boundary and the *safety-zone boundary*. Drivers never willingly enter the dread zone. The safety-zone boundary is the point of no return, at which there is nothing the driver can do to avoid a crash. The *safety zone* encompasses the comfort, discomfort and dread zones. Beyond the safety-zone boundary is the *mitigation zone*. In this zone, the driver or driver support systems may mitigate the consequences of a crash, but not avoid it. Each of these zones is a dynamic function of the driver and the situation. Finally, the safety margin comprises the spatiotemporal distance between the driver's vehicle and the point where the vehicle is predicted to cross the safety-zone boundary, given the kinematics and state of the involved vehicles (e.g., speed, relative distance and braking capacity) as well as the environment (e.g., friction).

1.3. Outcome measures in intersection research

Several studies of LTAP/OD scenarios use *post-encroachment time* (PET), illustrated in Fig. 3, in their analysis (Cooper, 1984; Nobukawa, 2011). The trajectories of vehicles on crossing paths define a rhomboid zone where their paths overlap. We call that zone the *encroachment zone*. PET is the time gap between the time when the first of the vehicles leaves the encroachment zone and the time when the second vehicle enters the encroachment zone. PET is quantified purely by geometry and timing.

PET is not a direct measure of the comfort-zone boundary because it is a post-hoc metric, not something directly perceived by drivers. However, since PET is a measure of what the driver actually did, the calculation of PET is sensitive to the presence of extra motives and resulting driver behaviors, such as cutting corners and/or increasing speed to increase vehicle separation. If the oncoming vehicle with the right-of-way is not braking, PET should provide an objective measure of the left-turning driver's safety margin.

1.4. This research in context

While the basic theory on safety margins, comfort zones, and extra motives is well established in the literature (Gibson & Crooks, 1938; Näätänen & Summala, 1974; Summala, 2007), prior work on driver behavior has rarely been quantified and interpreted using these constructs. Neither Gibson and Crooks (1938) nor Näätänen and Summala (1974) or Summala (2007) provide empirical quantifications of their described margins and boundaries. Among the articles that did use these constructs are studies of drivers' choices of time headway in vehicle-following situations (Brackstone & McDonald, 1999; Kesting & Treiber, 2008; Winsum & Brouwer, 1997), and gap acceptance while traversing an intersection (Caird & Hancock, 2002; Pietras, Shi, & Lee, 2006; Staplin, 1995). While these studies quantified specific aspects of driver behavior (headway and gap size), only Summala, Lappi, Pekkanen, Lehtonen, and Hietamäki (2012) addressed driver behavior from the perspective of comfort zones and safety margins. They used skin conductance and other psychophysiological measures

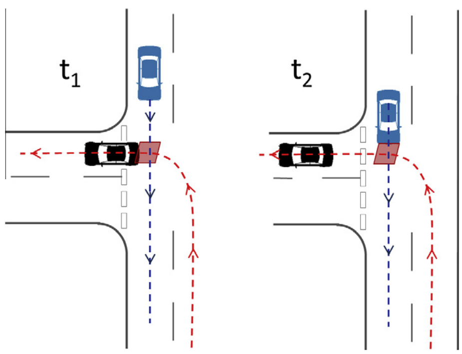

Fig. 3. Illustration of the two moments in time used in the calculation of PET when one vehicle turns left in front of an oncoming vehicle with the right-of-way. The red rhombus is the encroachment zone. PET = t_2–t_1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to quantify drivers' responses during an experimental task. The analysis showed the skin response to approximately follow a power function of the safety margin.

Although not explicitly providing comfort-zone boundaries, a paper by van der Horst (1990) describes a study of intersection conflicts; no conflict had a PET larger than two seconds. Similarly, van der Horst (1990) and Nobukawa (2011) describe PETs of two seconds or less to be safety-critical, while PETs larger than two seconds are described as normal driving. These findings led us to use two seconds as an anchor in our experimental design.

We do not know of any prior studies that quantitatively address the effects of extra motives on safety margins in turning scenarios. However, the U.S. CAMP studies quantified a boundary that drivers do not voluntarily cross for lead-vehicle situations (Kiefer, Salinger, & Ference, 2005; Kiefer et al., 2003). These studies varied lead-vehicle decelerations and asked drivers to brake at the last second (as late as they dared). It can be argued that this study created extra motives by asking drivers to be daring, and thus pushed drivers to define their dread-zone boundary.

Given the limited research relating driver behavior to comfort zones and safety margins, this study seeks to improve our understanding of the spatiotemporal space beyond the comfort-zone boundary. To accomplish this, we sought to quantitatively compare the comfort-zone and dread-zone boundaries in the LTAP/OD scenario. We suggest that the decision to stop and yield to the vehicle with the right-of-way marks the comfort-zone boundary under normal circumstances. In contrast, we suggest that when the driver is very hurried (that is, has an extra motive) the decision to stop and yield marks the dread-zone boundary for that scenario and traffic context.

These considerations lead us to propose two hypotheses: (1) Drivers will accept both a shorter PET and higher maximum lateral acceleration when hurried, compared to when driving comfortably; and (2) self-reports will reveal greater discomfort and feelings of risk when hurried.

To test these hypotheses, we varied the instructions to induce two different frames of mind in the participants, *comfortable driving* and *hurried driving*. A standard passenger vehicle and a balloon vehicle were equipped with throttle and brake control robots. Both vehicles were pulled up to a steady state speed of 50 km/h on a test track with an intersection. The participants got full control of the passenger vehicle approximately 20 m from the intersection, while the balloon vehicle continued at constant speed through the intersection. The participants were told to decide to turn left before or after the oncoming vehicle. The speed profile of the left-turning participant's vehicle was kept constant until the control handover on all runs.

Independent variables were driving condition (comfortable and hurried) and the *SetPET* for each run set by experimenters. The SetPET is the target value of the time gap (Fig. 3) for each run. It is the PET that would be observed if the driver were to maintain a reference trajectory. Dependent variables were the observed PET value and the maximum lateral acceleration. After each pass through the intersection, drivers completed a short questionnaire on perceived comfort, risk, hesitation, and likelihood that they would make the same decision again.

2. Method and materials

2.1. Participants

The study included 22 subjects (17 male, 5 female). The participants were recruited from a pool of employees at Autoliv Sverige AB ($n = 13$) and Volvo Car Corporation ($n = 9$). The inclusion criteria for all participants were that they should be between 25 and 65 years old and drive more than 5000 km per year. All drivers participated during their paid working hours, but were otherwise uncompensated. Participants' ages ranged from 25 to 61 years ($M = 49.7$, SD = 8.4 years). On average, participants had many years of driving experience ($M = 31.3$ years, SD = 8.1 years).

2.2. The intersection and apparatus

An artificial T-intersection was created at the airfield in Vårgårda, Sweden. The intersection had no traffic lights but had barriers on both the primary and the secondary roads to minimize drivers' ability to cut the corner, Fig. 4 (left). On the primary road, each lane was 3.5 m wide, while the minimum lane width on the secondary road was 3.8 m.

Fig. 4. The test-track intersection (left), and the balloon car used in the study (right).

The oncoming vehicle, herein called the Principle Other Vehicle (POV), was a computer-controlled self-propelled full-sized balloon vehicle (Fig. 4, right). The POV drives on a low-profile (height 20 mm, width 30 mm) rubber rail. The POV weighs approximately 65 kg, is 1.8 m wide and 1.8 m high.

In this study, the POV started at the same distance (150 m) from the center of the intersection in every trial and accelerated from zero to steady-state 50 km/h in 80 m. POV instrumentation included a longitudinal-position sensor and a 100 Hz differential GPS positioning system (Racelogic VBOX). The starting time of the balloon vehicle was manipulated as a function of the start time of the subject vehicle (robot) to produce the desired SetPET.

The participant vehicle, called the Subject Vehicle (SV), was a 2012 Volvo V50 with an automatic gearbox. To control the separation between the two vehicles, the SV was equipped with a throttle control robot, ensuring repeatability within and between participants. The SV always started at the same distance from the intersection (approximately 265 m), after which the throttle control robot accelerated to reach a steady-state speed of 50 km/h in 85 m. The vehicle kept the steady-state speed for approximately 120 m.

To simulate a vehicle slow-down maneuver when approaching the intersection, the SV was also equipped with a brake robot which initiated a constant deceleration. The brake robot was activated at a predetermined position (approximately 60 m) from the intersection. Both the throttle control and the brake robots were released at a predetermined position with respect to the center of the intersection; we call this point the *release point*. The release point was approximately 20 m from the center of the intersection. After the release point the driver had full control of the vehicle. The driver could, however, stop or slow down the vehicle at any time by pushing the brake pedal to override both the throttle and brake control robots. The driver also had full control of steering throughout the experiment. When the brake control robot gave full control to the driver there was a short (approximately 1 s) low-amplitude whine from the robot, as well as a (just) noticeable deceleration jolt of the vehicle. During on-track training the drivers were taught to identify these cues to the control handover.

2.3. The driving task

Drivers were instructed to make a left turn at the intersection. To make the turn they had to decide whether to turn before or after the POV. Each drive took approximately one minute from the time the SV started moving until the driver completed the turn and stopped the vehicle.

2.4. Experimental design

The repeated-measures experiment manipulated two independent variables. The first was driver behavior in the LTAP/OD scenario in two conditions: (1) comfortable driving and (2) hurried driving. Every driver drove all the runs in a fixed sequence, with the comfortable condition preceding the hurried condition. The order of the two conditions was not counterbalanced because it was expected that the hurried condition would strongly influence subsequent driving behavior in the comfortable condition, but that the relatively normal driving in the comfortable condition would have relatively little influence on subsequent hurried driving.

In the comfortable driving condition, drivers were instructed to make the left turn as they would in their normal everyday driving, for example, when on the way to/from work or to the grocery store. They were told to try to feel comfortable and safe when turning in front of the POV or, if they didn't, to wait and turn after it.

In the hurried driving condition, the participants were instructed to make the left turn as they would when in a hurry, that is, as if they were very late for an important meeting such as a job interview. Using the language introduced by Summala (2007), in the hurried driving condition we studied driver behavior when they had extra motives: they were in a hurry.

The second independent variable was the SetPET – the target value of the gap (Fig. 3) for each run that would be observed if the driver were to maintain a reference trajectory. The reference trajectory is the average of nine trajectories taken by three drivers in a series of pilot runs turning in front of the balloon vehicle (three times each) with a 'comfortable and safe' mindset. If the drivers in the study had followed the reference trajectory, the observed PET would equal the SetPET. Note that the observed PET is the PET that the individual driver created by turning while being exposed to the SetPET for a specific run (see Table 1). The experimenter in the control room created the SetPET for each experimental run by manipulating the relative start times of the throttle control robots in the subject and balloon vehicles.

2.5. Dependent variables

2.5.1. Electronically collected behavioral variables

Two dependent behavioral variables were used in the analysis. First, the observed PET value was calculated for each run. Second, lateral acceleration of the SV was obtained. The maximum lateral acceleration for each run was calculated.

2.5.2. Self-report variables

After each run, the driver was asked to answer five questions relating to the turn he or she had just made. These questions elicited the participant's subjective evaluation of comfort and risk for each turn. The wording of four of the questions

Table 1
All runs in the experiment for a representative participant. Run 13 and run 19 are the final Go decisions in this driver's set of runs in the comfortable and hurried conditions. They define this driver's comfort- and dread-zone boundaries. The two arrows show the runs used to establish the initial SetPET values for the Comfort iterative and Hurried iterative conditions.

Run #	Condition	SetPET (s)	Go/NoGo	PET (s)	Maximum lateral acceleration (m/s^2)	
1	Training: manual					
2	Training: SV robot					
3	Training: SV robot					
4	Training: SV robot					
5	Training: SV + BV robot	4.0	Go	2.7	2.8	
6	Training: SV + BV robot	4.0	Go	2.9	2.8	
7	Comfort preset	3.0	Go	1.9	2.7	
8	Comfort preset	2.0	NoGo		1.9	
9	Comfort preset	4.0	Go	3.5	2.9	
10	Comfort preset	1.0	NoGo		1.6	
11	Comfort iterative	2.4	NoGo		1.4	
12	Comfort iterative	2.8	Go	2.0	2.9	
13	Comfort iterative	2.6	Go	2.0	2.6	Comfort-zone boundary
14	Comfort iterative	2.4	NoGo		1.8	
15	Hurried iterative	1.4	Go	2.3	5.2	
16	Hurried iterative	0.4	NoGo		2.2	
17	Hurried iterative	0.8	NoGo		2.2	
18	Hurried iterative	1.2	Go	1.8	5.2	
19	Hurried iterative	1.0	Go	1.3	3.9	Dread-zone boundary
20	Hurried iterative	0.8	NoGo	1.2	4.0	

depended on whether a driver turned in front of the POV (Go decision) or let the POV pass and turned after (No-Go decision): for example, *How comfortable was your turn?* (after a Go decision) and *If you had turned in front of the balloon vehicle, how comfortable would you have been?* (after a No-Go decision). The questions as they were asked after a Go decision are shown in Table 2.

All questions were answered using a two-step rating system (Heller, 1982) that consists of five main categories each with three subcategories (Fig. 5). The same 15-item rating scale was used, with custom categories, for all five questions (see Table 2).

Table 2
Results of the analysis of the five self-report questions administered after each run for the comfort-zone and dread-zone boundaries (the last Go-decision in the comfortable and hurried driving conditions respectively). For each question the mean and standard deviation is shown, as well as the results of the comparison of means. A 15-point scale was used for the rating ($N = 22$).

Self-report questions for Go decisions	Rating scale [1 … 15]	t (21)	P	Driving conditions			
				Comfortable driving		Hurried driving	
Question				M	SD	M	SD
(1) How comfortable was your turn?	Very comfortable … very uncomfortable	−2.3	.032	5.6	2.3	7.1	2.5
(2) How risky was your turn?	Not very risky … very risky	−2.9	.009	5.1	2.2	7.1	3.0
(3) How difficult was it to make the decision to turn in front?	Very easy … very difficult	−2.3	.029	5.0	2.5	6.1	2.2
(4) How much did you hesitate in making the decision to turn in front?	Very low … very high	−2.9	.008	4.6	2.3	5.6	2.2
(5) What is the likelihood of your making the same decision the next time you are in the same situation?	Very unlikely … very likely	1.6	.115	11.1	2.3	10.0	2.6

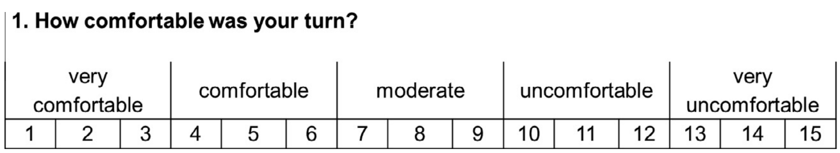

Fig. 5. The 5 × 3 rating scale for the five basic questions asked after each run for, as an example, the question "How comfortable was your turn?".

2.6. Procedure

Before arriving at the airfield, each participant filled in three background questionnaires: (1) a demographics questionnaire, (2) an Arnett Inventory of Sensation Seeking (AISS) questionnaire, and (3) a Driving Behavior Questionnaire (DBQ). They were told that the aim of the experiment was to inform our understanding of drivers' comfort zones when making a left turn at an intersection where a vehicle with the right-of-way approaches from the opposite direction. They were also told they would have to decide whether to turn before or after the balloon vehicle.

In the following sections the drivers' actual runs – passes through the intersection – are described, including on-track training and the actual experiment. Table 1 shows all runs, in the order they were performed, for a representative participant. The following text refers to Table 1 to illustrate the on-track procedure.

2.6.1. Training

On-track training consisted of three different training scenarios (Table 1, runs 1–6) to get familiar with: (1) the intersection and SV (without the throttle-control robot and the balloon vehicle), (2) the throttle-control robot in the SV (without the balloon vehicle), and (3) the whole test setup, including the approaching balloon vehicle. Every training scenario was repeated until the drivers said they felt comfortable with the current task and the vehicle. The average number of training runs across the three training scenarios was 7.2 (SD = 1.6).

2.6.2. The method of adjustment

For both the comfortable and the hurried conditions, the SetPET was manipulated according to a pre-defined iterative procedure, adapted from the method of adjustment used by Fechner (1860) and Gescheider (1997); see Table 1 and Fig. 6. In this procedure, experimenters adjust the level of a stimulus in a stepwise and iterative "up-down" procedure to determine the level of an implicit threshold. The thresholds we sought were the level of the PET and maximum lateral acceleration at which drivers tended to transition from Go decisions to No-Go decisions. Thus, the iterative procedure of the method of adjustment provided a pair of observed PETs and maximum lateral accelerations, one for the comfortable condition and one for the hurried condition. In the analysis we treat these transition runs as the comfort and dread-zone boundary, respectively.

To minimize the in-vehicle time for the participants, the comfortable condition was divided into two stages: (1) four preset SetPETs (Table 1, runs 7–10) and (2) the iterative adjustment of SetPET (Table 1, runs 11–14). Since the iterative adjustment provided a starting point for the hurried condition, only the iterative approach was required to determine SetPET in the hurried condition (Table 1, runs 15–20). Each run took from four to seven minutes to complete, including the administration of questionnaires.

2.6.3. Comfortable driving – preset SetPETs

For the preset stage, a predefined set of four SetPETs was used: 4 s, 3 s, 2 s, and 1 s. (A pilot study was run before the main experiment to determine these SetPET levels.) The order of the four SetPETs was balanced across the participants using a Latin Square. Participants were randomly assigned to the different orders of the SetPETs. The aims of the preset stage were

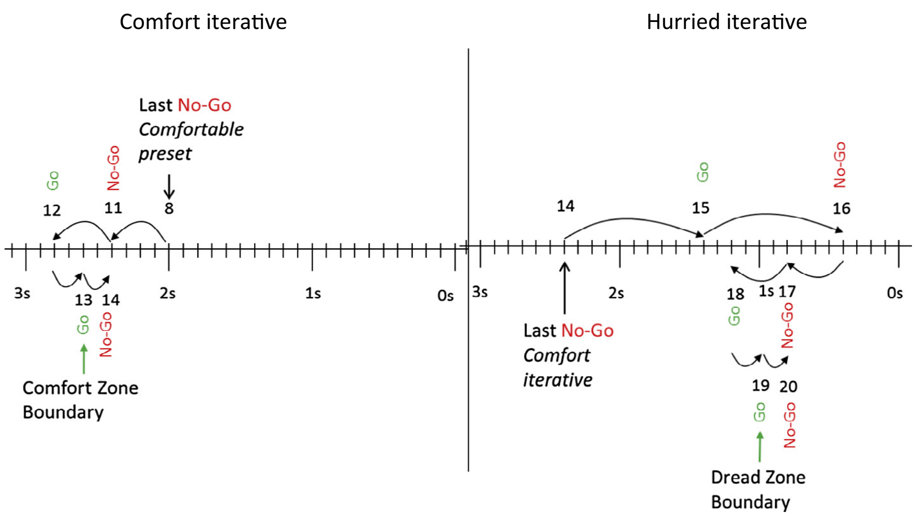

Fig. 6. Left: The iterative adjustment procedure in the comfortable condition. The numbers are references to the run numbers in Table 1. Right: The iterative adjustment procedure in the hurried condition. The numbers are references to the run numbers in Table 1.

(1) to familiarize the drivers with the experiment setup, (2) to get data to study potential order effects, and (3) to get a coarse characterization of the safety margins (SetPET) that drivers would adopt.

2.6.4. Comfortable driving – iterative SetPET adjustment

The driver's behavior in the preset stage was used to inform the initial SetPET used in the iterative adjustment stage. The aim of the iterative adjustment was to zero in on the SetPET threshold at which the driver tended to make No-Go decisions.

The No-Go SetPET from the preset stage (Fig. 6, left; Table 1, run 8; SetPET = 2.0 s) was used as the starting point. The SetPET was increased by 0.4 s until a SetPET with a Go decision was found (Fig. 6, left; Table 1, run 12; SetPET = 2.8 s). Then, this first Go SetPET was decreased in smaller steps (0.2 s), until finally the driver made a No-Go decision (Fig. 6, left; Table 1, run 14; SetPet = 2.4 s). The last Go and No-Go decisions (Fig. 6, left; Table 1, runs 13 and 14; SetPET = 2.6 s and 2.4 s) are assumed to bracket the driver's threshold between Go and No-Go. We call the Go run on the upper bound of the threshold in the comfortable condition the comfort-zone boundary (Table 1, run 14, PET column; SetPET = 1.8 s). We use two parameterizations of the comfort-zone boundary: (1) the observed PET at the comfort-zone boundary (PET_{CZB}) and (2) the observed maximum lateral acceleration at the comfort-zone boundary ($MaxLatAcc_{CZB}$). In the example shown in Table 1, the comfort-zone boundary was defined by run 13 (PET_{CZB} = 2.0 s and $MaxLatAcc_{CZB}$ = 2.6 m/s^2).

2.6.5. Hurried driving – iterative SetPET adjustment

The anchor for the hurried condition was the final No-Go SetPET from the iterative adjustment stage in the comfortable condition (Fig. 6, left; Table 1, run 14; SetPET = 2.4 s). For the iterative adjustment stage for the hurried condition, this SetPET was decreased by one second until a SetPET with a No-Go decision was found (Fig. 6, right; Table 1, run 16; SetPet = 0.4 s). The reason for using a one-second step in these iterations was to shorten the in-vehicle time for the drivers. The SetPET at this new No-Go decision was then increased in 0.4 s steps until the driver started to turn in front of the POV (a Go decision; Fig. 6, right; Table 1, run 18; SetPET = 1.2 s). Finally, the SetPET was decreased in 0.2 s steps until a No-Go decision was found (Fig. 6, right; Table 1, run 20; SetPET = 0.8 s). The last Go and No-Go decisions (Fig. 6, right; Table 1, runs 19 and 20; SetPET = 1.0 s and 0.8 s) are assumed to bracket the driver's threshold between Go and No-Go. We call the observed PET for the Go run on the upper bound of the threshold in the hurried condition the *dread-zone boundary*. The two dread-zone boundary parameterizations are the same as for the comfort boundary, but PET and maximum lateral acceleration are taken at the dread-zone boundary (Table 1, run 19; observed PET = 1.3; observed maximum lateral acceleration = 3.9 m/s^2). We denote them PET_{DZB} and $MaxLatAcc_{DZB}$.

2.6.6. Number of runs and the end of the experiment

Because we tailored the trials to the driver's Go/NoGo decisions, some drivers experienced more trials than others. For the comfortable condition, the average number of runs was 8.2 (SD = 1.7), with 6.5 (SD = 2.7) for the hurried condition. Due to the use of the iterative method-of-adjustment procedure, the runs differed in terms of quantity and SetPET across participants. Accordingly, it is not possible to assess sequence effects across participants.

At the end of the experiment, the participants were thanked for their participation and debriefed. The entire experiment lasted for approximately 3.5 h (range 3.0–4.0 h).

2.7. Data processing

Data from the SV and the POV were synchronized after data collection. Due to intermittent loss of differential GPS connection, parts of some SV and POV trajectories (positions) were reconstructed using speed from the GPS and the parts of the trajectory that had high quality position data.

3. Results

The data to calculate PET for two of the drivers were corrupted during data collection. As a result, there are 20 sets of PET values and 22 sets of maximum lateral acceleration. As hypothesized, drivers adopt shorter safety margins (PETs) and accept higher lateral accelerations when in a hurried state, compared to when driving comfortably. The results from the self-report questionnaires between runs are consistent with these findings.

3.1. The dread-zone boundary is quantitatively different from the comfort-zone boundary

3.1.1. Comparing conditions across drivers

As shown in panels A and B in Fig. 7, the repeated-measures paired differences for maximum lateral acceleration were not normally distributed. Accordingly, the pairwise differences for both PET and maximum lateral acceleration were analyzed using the Wilcoxon signed ranks test. The signed ranks test is more conservative than the more familiar within *t*-test.

The Wilcoxon test found that the PET at which drivers decided to turn in front of the oncoming POV was significantly different in the comfortable and hurried driving conditions (Wilcoxon $Z = 3.89$, $p < 0.001$, Fig. 7A). All comfortable – hurried pairwise differences were positive, indicating that, as expected, the PET was consistently greater for the comfortable condi-

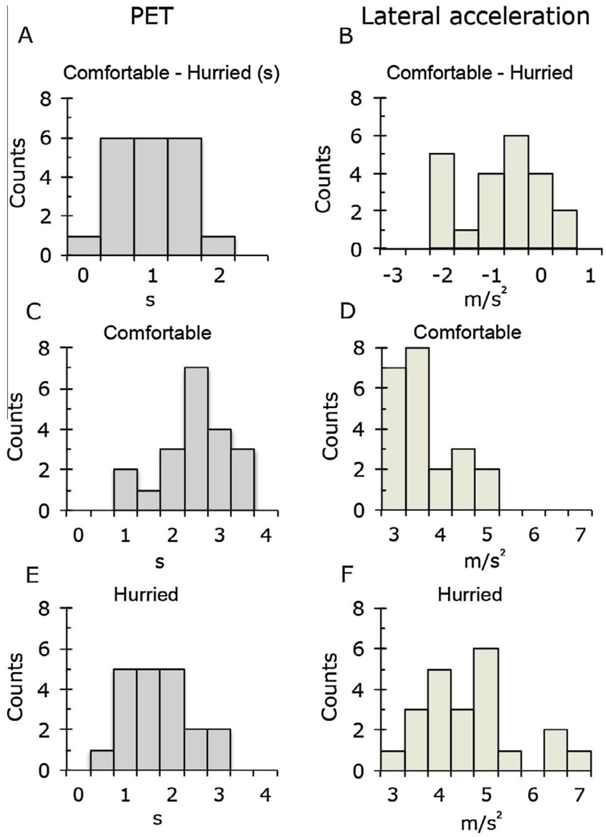

Fig. 7. Histograms of the paired differences (comfortable vs hurried) of PET (A) and maximum lateral acceleration (B) for the shortest PET at which the drivers turned in front of the POV ($N = 20$). (C and D) Histograms of observed values in the comfortable condition. (E and F) Histograms of observed values in the hurried condition.

tion. The median (mean) values for PET were 2.26 (2.22) s in the comfortable condition (Fig. 7C) and 1.50 (1.47) s in the hurried condition (Fig. 7E).

Similarly, the Wilcoxon test found a significant difference in maximum lateral acceleration between the conditions (Wilcoxon $Z = 3.85$, $p < 0.001$, Fig. 7B). Most, but not all, of the pairwise differences were negative, indicating that, as expected, the maximum lateral acceleration tended to be lower in the comfortable condition. The median (mean) values for maximum lateral acceleration were 3.23 (3.39) m/s^2 in the comfortable condition (Fig. 7D) and 4.12 (4.40) m/s^2 in the hurried condition (Figs. 7F).

3.1.2. Simple linear regression

Given the differences in both PET and maximum lateral acceleration between the two boundaries found in the previous section, linear regression analysis was used to examine the relationship between comfortable and hurried driving. Fig. 8 plots the PET parameterizations of the drivers' comfort-zone boundaries on *X* and those of their dread-zone boundaries on *Y*. A best-fit simple linear regression model was constructed to predict the PET at the dread-zone boundaries (response variable) given the PET at the comfort-zone boundaries (predictor). The regression (Eq. (1); the black solid line in Fig. 8) is significant, $F(1,18) = 23.7$, $p < 0.005$, $r^2 = 0.57$. As expected, drivers with larger comfort-zone boundaries have predictably larger dread-zone boundaries. Further, the model (Eq. (1)) indicates that PET values when the drivers are hurried are approximately 70% of the values when they are comfortable. The intercept is statistically equivalent to zero.

$$\mathrm{PET_{DZB}} = -0.07 + 0.69 \cdot \mathrm{PET_{CZB}} \quad (1)$$

Similarly, the simple linear regression on the drivers' maximum lateral accelerations (Eq. (2), Fig. 8, right) found a significant relationship, $F(1,20) = 12.8$, $p < 0.005$, $r^2 = 0.38$. As revealed by Eq. (2), the relationship between the two boundaries appears to be completely captured by the Wilcoxon test: the offset is constant, approximately 1.1 m/s^2, regardless of the value of the comfort-zone boundary.

$$\mathrm{MaxLatAcc_{DZB}} = 1.11 + 0.97 \cdot \mathrm{MaxLatAcc_{CZB}} \quad (2)$$

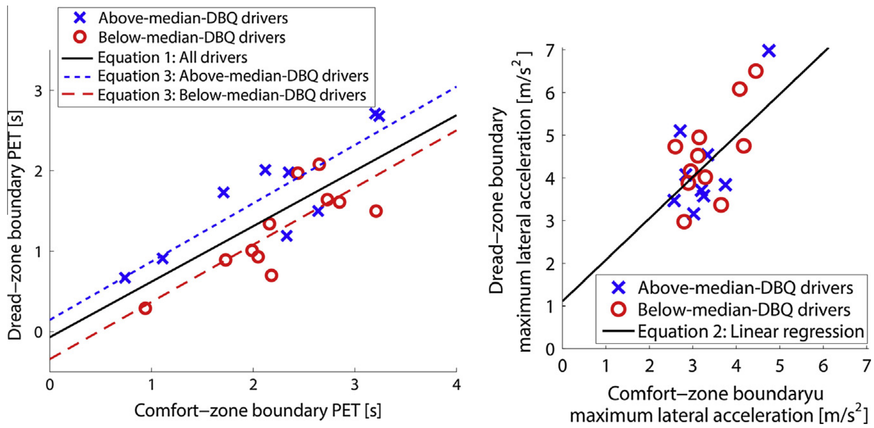

Fig. 8. The left and right panels show the observed PET and maximum lateral acceleration, respectively, at the comfort zone and dread-zone boundaries for 20 drivers.

3.1.3. Differences in DBQ ranking: multiple linear regression

Multiple linear regression was used to study potential covariates in demographics or driver traits (as captured by the Driver Behavior Questionnaire (DBQ) and the Arnett Inventory of Sensation Seeking (AISS) Questionnaire). No significant model improvement was found when introducing driver demographics (gender, age, driving experience) or the AISS. However, introducing a dummy variable (MedianDBQDummy) representing the median split in DBQ total scores (drivers above the median were assigned 1; drivers below the median were assigned 0) significantly improved the model fit to the PET data, $F(3,19) = 14.4$, $p < 0.001$, $r_a^2 = 0.69$; Fig. 8. Eq. (3) shows the multiple linear regression model.

$$\mathrm{PET_{DZB}} = -0.36 + 0.72 \cdot \mathrm{PET_{CZB}} + 0.52 \cdot \mathrm{MedianDBQDummy} \tag{3}$$

The regression model in Eq. (3) indicates that drivers with below-median DBQ scores accept smaller safety margins (lower $\mathrm{PET_{DZB}}$) than drivers with above-median DBQ scores. Similar regression analyses were run for each of the three sub-factors of DBQ. None proved significant. Regression analyses using median split were also run for the lateral acceleration data. Adding these factors as predictors did not improve the fit of the simple linear regression model relating $\mathrm{MaxLatAcc_{DZB}}$ to $\mathrm{MaxLatAcc_{CZB}}$ (Eq. (2)).

To further understand the differences between the comfort- and dread-zone boundaries with respect to PET between the two levels of DBQ, we studied the difference between the two DBQ levels for the two conditions. A two-way within-between ANOVA found the interaction between the two levels of DBQ and the experimental condition to be significant ($F(1,28) = 8.93$, $p < 0.01$; Fig. 9). Experimental condition (i.e., comfortable or hurried driving) was the repeated factor and the DBQ level (DBQ median-split) was the between factor. As Fig. 9 shows, there is no difference in $\mathrm{PET_{CZB}}$ but a large difference in $\mathrm{PET_{DZB}}$ is observed across the DBQ median split.

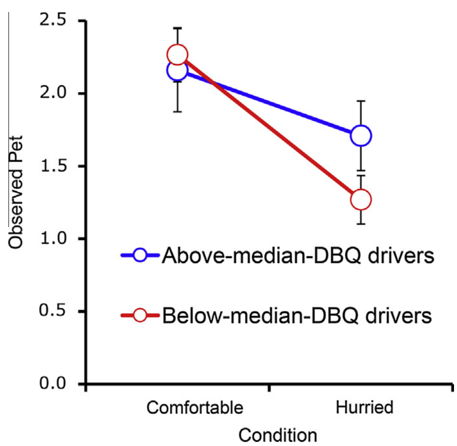

Fig. 9. Interaction plot showing the differential influence of the hurried condition between groups of drivers defined by the median split in total DBQ scores. Error bars represent the standard errors of the mean.

3.1.4. Evaluation of the effect of run order

As the order of the comfortable and hurried conditions was not balanced across participants in the experiment, an evaluation of the effect of run order (sequence effect) was performed using a two-way ANOVA. The four SetPET values (1 s, 2 s, 3 s, and 4 s) for the preset stage in the comfortable condition were used, since their order was balanced across drivers. The two-way ANOVA failed to reject the null hypothesis ($F(3,57) = 2.66$, $p > 0.05$). The sequence of SetPET had no influence on observed PET.

3.2. Drivers' assessment of comfort- and dread-zone boundaries

The five self-report questions administered after every run were compared between the two conditions using paired *t*-tests, treating self-report data as interval scale data (Heller, 1982). Summary statistics of the self-report measures between the comfort-zone boundary and the dread-zone boundary are shown in Table 2. The paired *t*-tests compare the differences (comfortable/hurried) observed at the comfort- and dread-zone boundaries, respectively. Four of the five questions showed a significant effect. The first two responses reveal that drivers rated the turn at the comfort-zone boundary to be significantly more comfortable and less risky than the turn at the dread-zone boundary. The third reveals that they found the decision to turn to be less difficult at the comfort-zone boundary than at the dread-zone boundary. The fourth indicates there was significantly less hesitation before turning in front of the oncoming vehicle in the comfortable condition. However, the difference between the two conditions was not significant for the question on the likelihood of making the same decision again.

3.3. Sensitivity analysis

As a manipulation check, the bivariate Pearson correlation was used to quantify the impact of the variability of the deceleration of the SV brake robot (predictor) on PET (response) at the final Go decision for each driver. We expected that variability in the brake robot deceleration would have a significant effect on the observed dread-zone boundary. However, the results show that there is no significant correlation between the average lateral acceleration while the brake robot was active and the PET for the last Go decision. This may be interpreted in two ways. Either the decision to turn before or after the oncoming vehicle was made before the start of the braking, or the differences in speed and position at the time of the release (20 m before the intersection center) were not large enough to have a consistent effect on the observed values of PET.

4. Discussion

This paper expands on the established concept of drivers' adoption of safety margins in traffic, by creating a more fine-grained, quantifiable series of definitions for the spatiotemporal space beyond the comfort-zone boundary, but before the point of no return (when a crash is unavoidable). Although this is not the first study to seek to quantify various aspects of safety margins, most previous work has focused on the comfort zone, in which the driver feels safe, and seeks to remain. The concept of extra motives (such as driving under time pressure; Näätänen & Summala, 1974) has also been applied to explain that drivers can push themselves past their comfort-zone boundary. The newly defined discomfort and dread zones lie beyond the comfort zone. Although drivers with extra motives will cross the comfort-zone boundary into the discomfort zone, the dread-zone boundary is a threshold which drivers will not cross, even with extra motives. We have demonstrated the utility of both boundaries by quantifying how they differ within the context of making a left turn in an unsignalized intersection during a controlled test-track experiment. We argue that the dread-zone boundary in particular has great potential for informing automotive safety research and the design of advanced driver assistance systems (ADAS; Benmimoun, Ljung Aust, Faber, & Saint Pierre, 2011; Dozza, 2010) and autonomous vehicles (VCG, 2013).

4.1. Comfort- and dread-zone boundaries

4.1.1. Comfort- and dread-zone boundaries: PET and maximum lateral acceleration

In this paper we have defined the comfort- and dread-zone boundaries in our LTAP/OD experiment as each drivers' last Go decision in the iterative method of adjustment for the comfortable and hurried mindset. When in a hurried mindset, drivers appear to be willing to reduce the gap (PET) by approximately a third, regardless of the value of the comfort-zone boundary. In contrast, no such relationship was found for the maximum lateral acceleration parameterization. It appears that drivers are willing to allow acceleration to increase by a constant amount, approximately 1 m/s^2, regardless of the acceleration at their comfort-zone boundary. In future quantifications of comfort- and dread-zone boundaries, it would be advisable to evaluate several different parameterizations of these boundaries to gain further understanding of the effects of extra motives on drivers' tacit choices in everyday driving.

4.1.2. Comfort- and dread-zone boundaries: self-reports

Self-reports show that the drivers voluntarily adopted different safety margins with different feelings of comfort and risk, in the same controlled setting, when they had extra motives. They pushed themselves past the comfort boundary toward more discomfort and a feeling of higher risk – into the discomfort zone. They also reported they had less trouble making the decision to turn and hesitated less at the comfort-zone boundary than at the dread-zone boundary. This is in line with what would be expected.

The only question that did not elicit different responses across conditions asked drivers about the likelihood of making the same decision again in the same situation. It appears that driver confidence in the appropriateness of their decisions was not influenced by the manipulation of comfort. This is a somewhat surprising result, since it may be hypothesized that the driver would be less decisive in turning before an oncoming vehicle with smaller safety margins (i.e., at the dread-zone boundary). However, it may be that the internalized incentive in the hurried mindset (extra motive) counteracted the indecisiveness.

4.1.3. Predictive value of grouping drivers by DBQ score

Our analysis further shows that there are individual differences in the values of the comfort and dread-zone boundaries for both PET and maximum lateral acceleration. These differences are manifest both within and between the driving conditions. First, the median split of the Driver Behavior Questionnaire (DBQ) significantly improved the prediction of PET_{DZB}, with PET_{CZB} as main predictor. This result demonstrates that drivers with below-median DBQ scores (whom we shall refer to as more rule-following drivers) accepted shorter PETs in the hurried condition than our relatively less rule-bound drivers. This result is counter-intuitive: The more rule-following drivers made riskier turns. A possible explanation is that rule-following participants are more willing to follow the experimenter's instructions to push themselves in the hurried condition. This result clearly needs confirmation in an independent study.

No relationships were found between the Arnett Inventory of Sensation Seeking and the pairwise differences in PET or maximum lateral acceleration between the two conditions. This result also needs confirmation in an independent study.

4.1.4. Order effects and fatigue

In this study the order of the driving conditions was fixed, with the comfortable condition always before the hurried condition. This sequence avoided the possibility that habituation to hurried driving would influence driver behavior at the comfort-zone boundary. Because the hurried condition followed the comfortable condition, the resulting dread-zone boundary may be closer to the safety-zone boundary (smaller safety margins) due to habituation. However, as there was little or no indication of an order effect in the four preset runs in the comfortable condition, habituation probably did not affect the outcome significantly. In a future study it would be interesting to run a replication of the comfortable driving condition after the hurried condition. We believe it is likely that the study would find evidence for habituation from hurried to comfortable driving.

The participants' time in the experiment vehicle was relatively long, three to four hours. Some drivers can be expected to have experienced some fatigue. Unfortunately, the method of adjustment used in the experiment does not lend itself to uncovering the effects of fatigue. The iterative adjustments were different for every participant and produced only one value per condition (the comfort- and dread-zone boundaries). We can only speculate about the role played by fatigue in this study. We suspect that fatigue may make some drivers more risk-averse (i.e., they choose larger safety margins) as they fall back on more comfortable and safe driving; on the other hand, others may become more casual about the risk posed by the balloon car (i.e., they choose smaller safety margins) due to habituation. If in fact some drivers were fatigued, and the fatigue influenced them in different ways, then our data has a larger between-driver variability then may be expected in real traffic. However, to try to counter the effects of fatigue, we often repeated the mind-set instruction throughout the hurried condition.

4.2. The method

4.2.1. Safety margins in a controlled vs. naturalistic setting

We conducted this experiment on a test track using a balloon car as the oncoming vehicle. Unlike the drivers of vehicles in a naturalistic setting, the autopilot of the balloon car did not modify its behavior in response to the driver's encroachment. It approached and passed the intersection at a steady speed of 50 km/h, even when confronted by an encroaching left-turning driver.

The safety margins (e.g., PETs) realized when two drivers interact during normal everyday LTAP/OD turns are a combination of the margins that both drivers accept. When drivers with the right-of-way realize that the anticipated encroachment may take them out of their comfort zones, they are likely to slow down to provide additional time for the left-turning vehicle to pass. Slowing returns drivers with the right-of-way to their comfort zones, resulting in an increase in the actual safety margin for both vehicles.

The only ethical way to observe this social interaction is to conduct on-road naturalistic observations. Nobukawa (2011) conducted a study of real-traffic LTAP/OD interactions. He measured the slowing-down of the vehicle with the right-of-way. This is a tacit form of social communication that diminishes the likelihood of a crash. For example, as the driver in the oncoming vehicle picks up cues that the approaching vehicle is about to turn, he or she will likely slow down (or brake hard) to avoid crashing. When this communication is lacking, the likelihood of crashes increases. Our experiment replicates the situation where there is no tacit exchange between the two drivers and the likelihood of a crash is relatively high. Since we kept the speed of the right-of-way POV constant, we avoided the complication, unavoidable in observational studies, of measuring the comfort-zone boundary of the driver of the POV.

4.2.2. Using mindset manipulation to study the effect of extra motives

The two conditions c*omfortable* and *hurried* were created by providing instructions to the participants to get them into the appropriate real-life mindsets. Some may see this as a shortcoming of the experimental design. The ethics of experimentation preclude providing real-life incentives like driving in real traffic. However, both the quantitative data (comfort- vs. dread-zone boundaries) and the self-reports on comfort and risk indicate that the hurried mindset succeeded in creating more aggressive driving.

When designing the study we considered using monetary incentives based on performance (e.g., competition-based), but decided against it to avoid game-like conditions. Indeed, a study by Newnam and Watson (2011) provides some evidence that monetary compensation induces less safe driving than voluntary participation does. We wanted to avoid such a bias. However, further research is needed to understand how internalized incentives of hurried driving are related to real-life hurrying.

4.3. The application of dread- and comfort-zone boundaries to vehicle safety

The introduction of the dread zone and its boundary, as well as the quantification of both the comfort- and dread-zone boundaries, is important from a pragmatic point of view: they can contribute to the development of advanced driver assistance systems (ADAS; Hummel, Kühn, Bende, & Lang, 2011; Benmimoun et al., 2011) and automated driving (AD) vehicles.

4.3.1. The design of advanced driver assistance systems (ADAS)

Traditional ADAS designs often reference the objective kinematics of proximity to the safety-zone boundary (Brannstrom, Sjoberg, & Coelingh, 2008). We argue that the design of ADAS should also include the comfort- and dread-zone boundaries. Drivers are unlikely to accept an ADAS intervention (warning and/or braking/steering control) while in the comfort zone. However, the probability of drivers accepting ADAS interventions is likely to increase monotonically in the discomfort zone as they approach the dread-zone boundary. We further argue that when the dread-zone boundary is crossed, all drivers should accept all interventions (e.g., braking or steering). When drivers cross into their dread zone they are closer to a crash then they would ever voluntarily allow themselves to get. Thus, if an intervention were to be activated, the driver should feel that the intervention is justified. In contrast, interventions before the drivers have crossed the dread-zone boundary may be perceived as nuisances or errors since drivers may merely be feeling discomfort, and may not yet feel that a crash is imminent. In fact, the feeling of discomfort may be voluntary if the driver had extra motives for crossing the comfort-zone boundary.

The tacit spatiotemporal limits of the comfort- and dread-zone boundaries are immediate and real to the driver and shape driving behavior. Thus, comfort- and dread-zone quantification can be used by the designers of ADAS to create systems that facilitate the selection of appropriate default settings in ADAS algorithms. However, due to large differences in safety margins between drivers, ADAS which automatically adapts to each individual may more accepted.

Another implication of the relatively large individual differences in comfort- and dread-zone boundaries is that unless ADAS are made adaptive (Jianqiang, Lei, Dezhao, & Keqiang, 2013), ADAS designers will likely have to choose conservative settings (intervening closer to the crash) or provide drivers with the ability to modify activation thresholds. However, driver-modifiable thresholds may not be practically implementable; since close-to-crash events are rare, drivers may not know what their preferences are, since they probably lack experience with this type of event. It is likely that the first ADAS addressing left turns in intersections (Lingeman, 2014) will have to intervene late, sacrificing effectiveness in order to be more acceptable to drivers. In the future, however, ADAS solutions may be able to improve effectiveness by adapting to individual drivers' traits, without compromising acceptability.

Continued experimental quantification of these boundaries, by means of test tracks, driving simulators, and naturalistic observations, can inform the design of ADAS alerting algorithms that drivers are likely to welcome, to purchase, and to heed. It is probable that some adaptation to individual differences will play a role in their acceptability.

4.3.2. Automated driving

Quantification of the comfort-zone and dread-zone boundaries can also be used to inform the development of automated driving at different levels of automation (SAE, 2014). The drivers of autonomous vehicles, along with all other road-users, expect autonomous vehicles to behave as if they were being driven by a person (Li, Shih-Jie, & Yi-Xiang, 2003; Markoff, 2010). By quantifying comfort- and dread-zone boundaries for a variety of contexts, developers of algorithms controlling automated vehicles can tune their vehicles to display acceptably human-like behaviors. For example, an automated vehicle making a left turn should stay in the comfort zone with respect to both maximum lateral acceleration and PET. Entering the discomfort zone may be acceptable in certain situations, while entering the dread-zone would never be accepted by drivers or surrounding traffic, except to avoid an imminent crash.

Due to the fact that the linear regression models of PET and maximum lateral acceleration between the two conditions had different characteristics (30% reduction versus a constant increase, respectively) designers of automated vehicles will likely need to consider a variety of comfort-and dread-zone parameterizations, particularly throughout the discomfort zone.

4.4. Future work

A natural next step is to evaluate comfort- and dread-zone boundaries for different intersection layouts (e.g., with/without a median barrier), cultures (e.g., US/Sweden/China) and vehicle speeds. Future work should also study the influence on the driver of cognitive demands unrelated to the driving task. We recommend that research on safety margins, gap acceptance, and infrastructure design all include the quantification of the dread-zone boundary. Finally, exploring the predictive power of driver traits (such as those captured by the DBQ) on driving, with and without extra motives, could further the understanding of the acceptance of, for example, ADAS interventions and AD designs. Several of these studies lend themselves to driving simulators.

Acknowledgments

This study was sponsored by the Swedish funding agency VINNOVA, the partners in the Driver Comfort Boundaries in Intersection Negotiation (DCBIN) project (Volvo Car Corporation and Autoliv Development AB), and the Swedish Strategic Transport Funding. We would like to thank the test track crew at Autoliv for their expertise in running the experiment, Regina Johansson, Christina Gullander, and Helen Herrera for support in the study execution, Sergejs Dombrovskis for support in post-processing of data, and Kristina Mayberry for language editing.

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